MONTHLY
WEATHER
REVIEW

VOLUME 92, NUMBER 6

JUNE 1964

A SYNTHESIS OF INTERPRETATIONS OF EXTRATROPICAL VORTEX PATTERNS AS SEEN BY TIROS [1]

WILLIAM K. WIDGER, JR.

ARACON Geophysics Company, Concord, Mass.

ABSTRACT

An attempt is made to integrate the existing knowledge, from some 28 published sources, with regard to the interpretation of satellite observed cloud vortex patterns. It is found that the model proposed by Boucher and Newcomb is generally valid, although certain elaborations seem reasonable. Characteristics of cloud patterns indicative of troughs rather than closed Lows have been determined by Rogers. It is found that information concerning pressure center positions, pressure departures from normal, future system movement, frontal positions, air mass conditions, surface and upper-level winds, and precipitation can often be deduced from the cloud patterns visible in the satellite pictures.

1. INTRODUCTION

The following discussion constitutes an attempt to integrate the existing published knowledge with regard to the interpretation of satellite observed cloud vortex patterns and certain other closely related meteorological phenomena. Included also are some deductions and comments of the author. The basic sources are listed in the references.

2. VORTEX PATTERN SEQUENCE

THE SEQUENCE OF CLOUD PATTERNS

There now seems little doubt as to the general validity of the model proposed by Boucher and Newcomb [2]. Serebreny et al. [23] state that their analysis "most definitely supports the cloud models presented by Boucher and Newcomb." However, certain elaborations of the model, such as the pre-occlusion stage proposed by Merritt [16] between the frontal wave and the beginning of the occlusion process, seem reasonable. Furthermore, not all cyclones follow this sequence. Lesse [13] reports that surface development may take place, without formation of a cloud vortex, in the absence of an upper closed Low. Usually, in such cases, unless an upper air trough or Low is present or develops, there will be a restriction on the extent of surface development. Jacobs-Haupt [10] indicates that Mediterranean-area cyclones are less apt to show spiral cloud patterns. Merritt [16] illustrates frontless vortices, cut off from the general zonal circulation, which may not have originated with a frontal wave. Studies of Boucher et al. [3] indicate many cyclones or troughs, and their associated cloud vortices do not really evolve from a frontal wave, and the first recognizable cloud pattern may be similar to any one of the first four stages described below.

THE FRONTAL WAVE STAGE

The initiation of the Boucher-Newcomb sequence is the broadening or bulging of the frontal band. Typically this is accompanied by slightly curving parallel bands poleward of the front, and a more reflective area of higher and deeper clouds just to the east of the wave crest, as shown in figure 1.

At this stage, the development is so meager that, as Boucher and Newcomb state: "This particular cloud configuration or one very similar to it has also been found in cases where neither wave nor front could logically be inferred, pointing to the need for exercising caution in the interpretation of cloud patterns." On the other hand, also as a corollary to the relatively insignificant appearance of this stage, the wave may often be hidden by a more extensive cloud sheet [2]. (The case discussed by Timchalk and Hubert [24] seems to be one such.) This is illustrated in figure 2. In any event, no visible distinct spiral

[1] The studies reported here were sponsored by the National Weather Satellite Center, U.S. Weather Bureau, under Contract No. Cwb-10630.

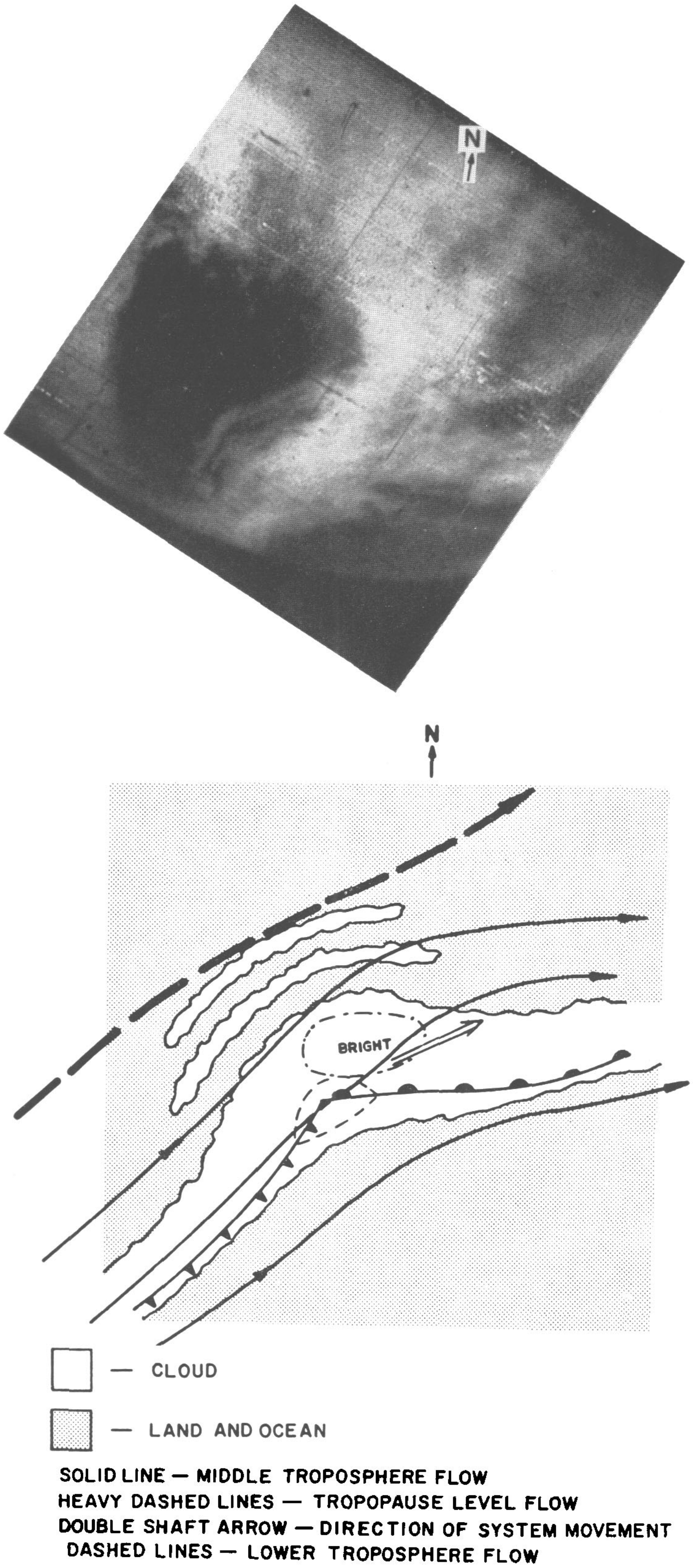

FIGURE 1.—Frontal wave (TIROS I wide-angle photograph; near 45°N., 175°E.; 0050 GMT, May 24, 1960).

pattern is to be expected at this stage [8] (unless the slightly bent cloud lines poleward of the main band are considered as a type of visible precursor). Even so, Madvig [14] has reported that the development may not be apparent in the synoptic data until 12 hr. after the bulge on the front can be discerned in the satellite pictures. Usually, at this stage, the development can be expected to be influencing only conditions near the surface and in the very lowest portions of the atmosphere.

If the field of view of a satellite pass does not include the center of an area of probable development equatorward and to the west of a major cyclone, evidence of any such developments may sometimes be noted near the edge of the photographed region in the form of a significant and otherwise unidentified cloud band or polar extension of an existing band such as that marked "E" by Winston and Tourville [28] in their figures 2 and 4.

In summary, pictures of areas synoptically and/or climatologically prone to cyclogenesis should be carefully examined for signs of wave development, whereas cloud patterns possibly indicating wave development outside such areas should be reviewed carefully before being accepted on face value without other substantiating evidence. Furthermore, the possibility of an incipient wave's dying out without significant development must always be considered; this seems to have been the fate of the western Atlantic frontal wave photographed from the Atlas 11c nose cone in August 1959. Another possibility is that of a stable wave moving along a front without significant increase in amplitude. These waves usually have little or no upper-level support in the form of a vorticity advection area.

PRE-OCCLUSION STAGE

As we proceed to the subsequent stages of development, we must realize that a continuity of progression, rather than discrete stages with precise boundaries, is to be expected in any storm development model. Accordingly, any attempt to distinguish arbitrarily between an advanced phase of one stage and an early phase of the next stage is impossible and has no real meaning.

As Boucher and Newcomb [2] have indicated, the transition from the wave to the partly occluded vortex is rapid and, consequently, only infrequently observed. Nevertheless, Merritt [16] has suggested the need of ". . . a further stage of development between the frontal wave pattern stage and the stage depicting the beginning of the occlusion process." The cloud pattern, illustrated in figure 3, shows a line of cloudiness lying poleward from the low pressure center of the open wave stage. As shown here, it seems likely that this line would typically be broader longitudinally than shown in Merritt's original schematic and that figure E–10 of Madvig [14] is very likely a pre-occlusion rather than an open frontal wave stage example. Madvig has pointed out in his figure E–10 that "The faint ring of cellular clouds surrounding the leading edge of bright clouds is interesting since it

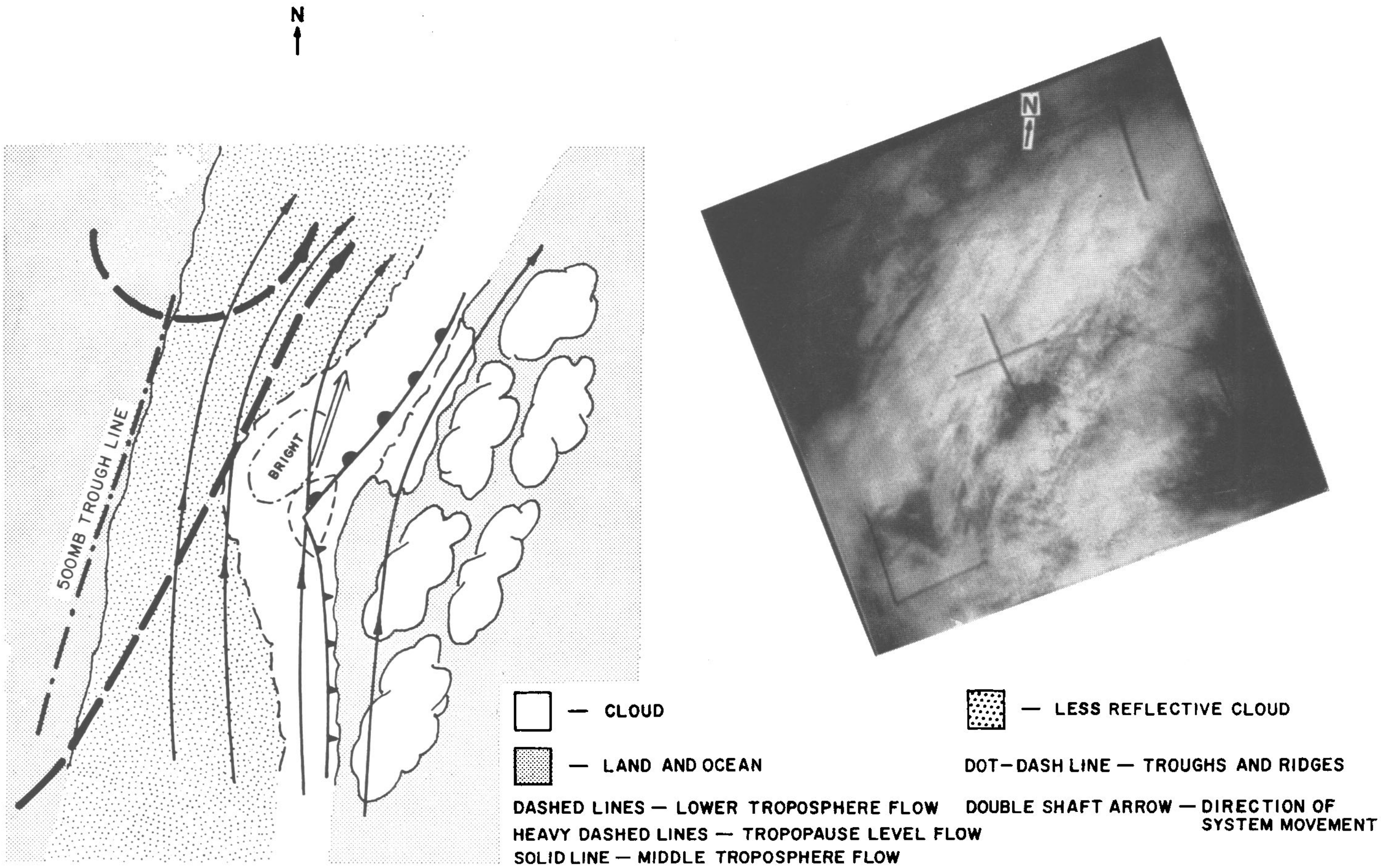

FIGURE 2.—Cloud-masked frontal wave (TIROS V wide-angle photograph; near 45°N., 85°W.; 1430 GMT, Sept. 4, 1962).

appears almost to be a reef of clouds in front of the entire open-wave structure." Perhaps the key feature of this stage is the significantly greater poleward bulging or cloud protuberance than in the frontal wave stage, retaining generally a longitudinal symmetry which disappears in the succeeding beginning-of-occlusion stage as the intrusion of the clear, dry air first becomes apparent.

At this stage, the circulation would in a typical case be influencing the lower atmosphere, but not yet reaching significantly to the 500-mb. level.

BEGINNING OF OCCLUSION STAGE

This stage is still within the period of rapid development, and observations appear to be scarce. As Boucher and Newcomb state (see fig. 4): ". . . there is now a noticeable asymmetry in the cloud pattern due to the intrusion of the clear area behind the cold front. At this stage also it is expected that the 'vortex signature' should appear as a spiral streakiness in the cloud pattern. This has been indicated by spiralling arrows in the schematic and can be readily seen in the TIROS photo." However, in many cases the contrast within the cloud pattern may be inadequate to permit seeing any pattern within the bright overcast area. These spiralling streaks suggest that by this stage there should be a significant trough, or even the beginning of a closed Low, at 500 mb. As Sherr [3] has shown, however, in this stage the cloud vortex is more frequently related to a surface than a 500-mb. center, and is normally located south and west of the related surface pressure center.

Another representative feature may be the cyclonic movement around the major cloud mass of the arching cloud bands formerly poleward of the Low.

Although the proximity to the margin of the pictures and to the coast make it difficult to be sure, it appears likely that the vortex shown by Serebreny et al. [23] in their figures 8 and 9 (orbital pass 691; approximately 55° N., 140° W.) may be another example of this stage.

Rogers [3] found bright, overcast, crescent-shaped cloud patterns (such as that illustrated in fig. 5, with the crescent outlined in dashed black, slightly outside to permit the cloud edge to be seen), at times resembling in geometric outline this or the next stage, to be associated with 500-mb. trough patterns rather than closed 500-mb. Lows. In such cases, the clouds depict the area ahead of the trough where the air is rising rather than the streamlines of the air flow. The pattern can often be identified by the abrupt termination of the crescent cloud pattern equatorward of a line west of the apparent circulation center (just north of the straight portion of the dashed black

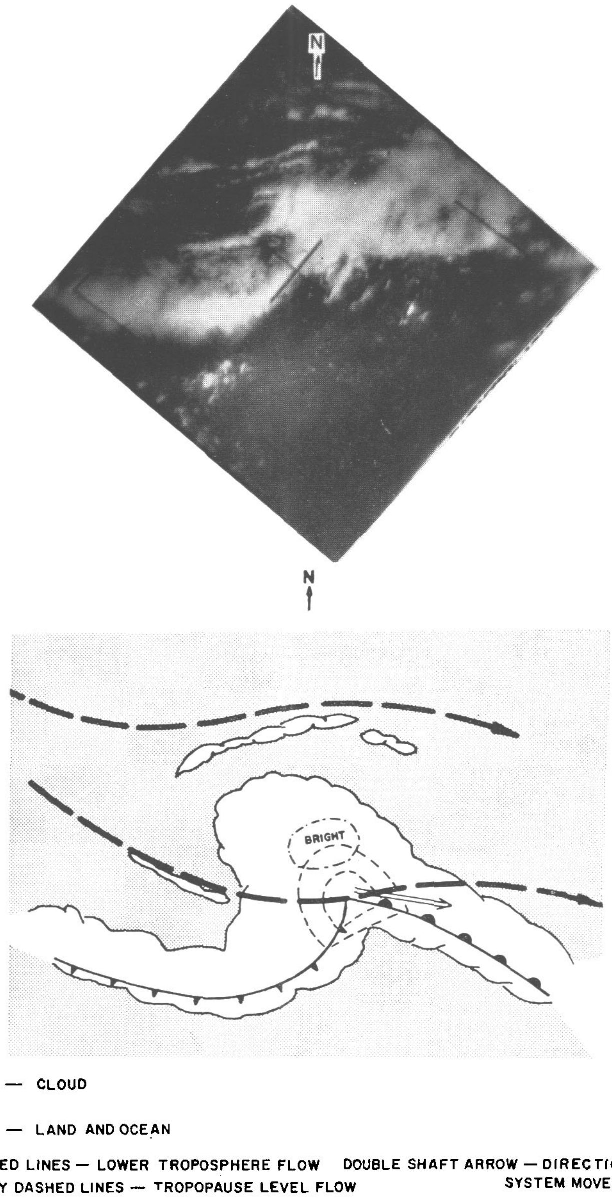

FIGURE 3.—Pre-occlusion (TIROS V wide-angle photograph; near 35°N., 65°W.; 1610 GMT, Aug. 23, 1962).

outline), with only scattered to broken lower-level cloudiness in the quadrant west and equatorward of the apparent center. As illustrated in figure 5, these crescent-shaped, bright overcasts are often accompanied by lower, frequently cumuliform, U-shaped or closed cloud patterns which appear to identify the surface pressure center.

OCCLUDING CYCLONE STAGE

For this and subsequent stages, the cloud patterns are sufficiently conspicuous and distinctive, and the available cases so numerous, that a number of studies have been made. That used by Boucher and Newcomb to illustrate this stage (their figs. 5a and b) has been discussed at length by Bristor and Ruzecki [4]. Another case, with an extremely similar appearance at this stage, has been

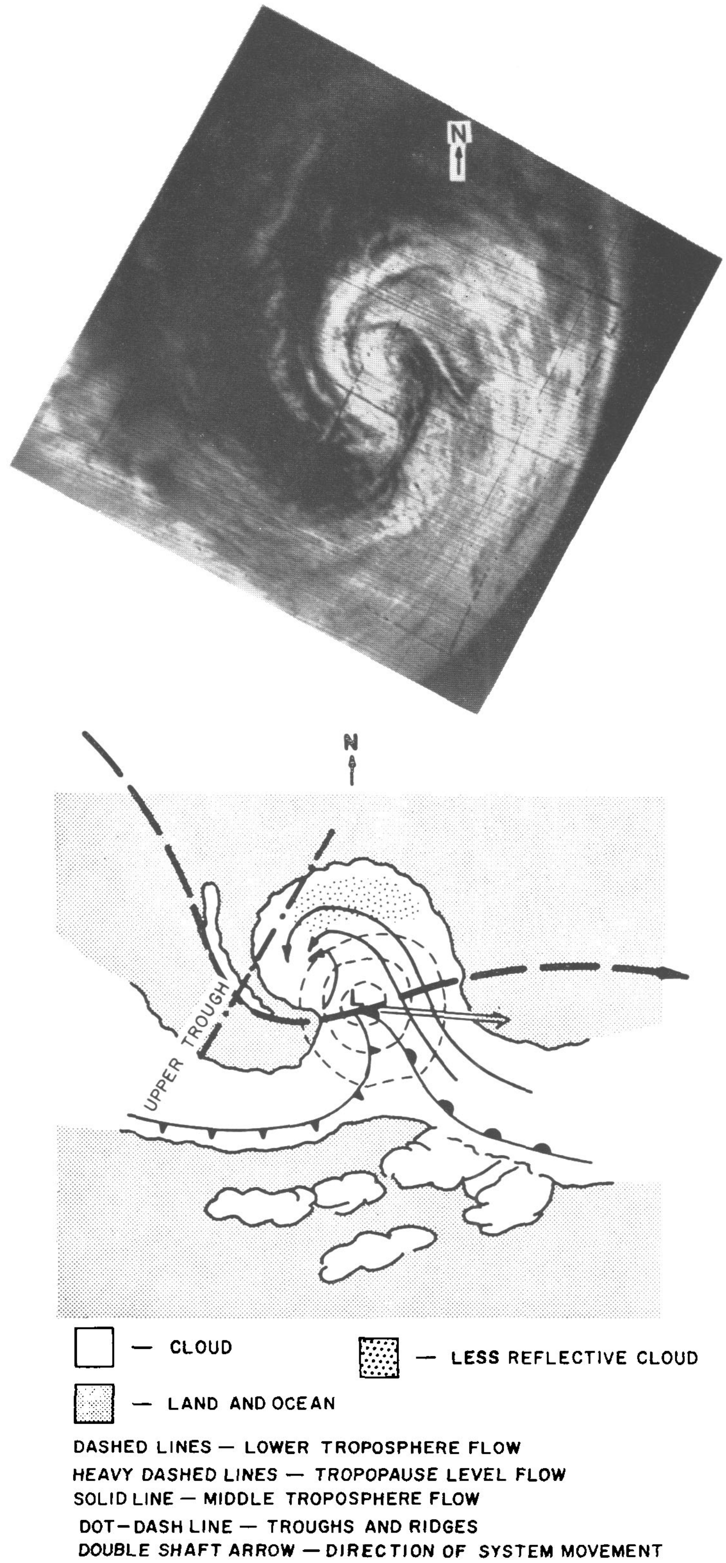

FIGURE 4.—Beginning of occlusion (TIROS I wide-angle photograph; near 55°S., 20°W.; 1408 GMT, Apr. 30, 1960; picture inverted to simulate Northern Hemisphere configuration).

studied both by Leese [13] and by Timchalk and Hubert [24].

The key feature at this stage is the very definite intrusion of the "clear" dry air eastward into the cloud mass behind the cold and occluded fronts, and the curvature of this dry and usually cold air poleward around the center of the associated Low. Boucher and Newcomb suggest that this stage is indicative of a significant circulation and is probably not typical of storms with only weak middle or upper-level circulations. In fact, a closed Low extending to 500 mb., and perhaps throughout the troposphere, would normally be expected. Sherr [3] found that vortex patterns at this stage usually had related pressure centers at both the surface and 500 mb. within 200 n. mi. of the vortex center.

The degree to which the dry air is essentially completely clear (fig. 6) as compared to being partially filled with convective cloudiness (fig. 7) seems to be a function of the humidity and stability of the cold air and of the surface under it.

In the case studied by Leese [13], it was found that the lowest central pressure at the surface occurred with a degree of dry air intrusion only slightly greater than that in the schematic in figure 6. This complements the studies of Sherr [3], who found vortices at this stage to have the greatest average departure (18 mb.) from the normal seasonal surface pressure for their location. The corresponding average 500-mb. departure was 530 ft.

Serebreny et al. [23] have suggested that, since the length and breadth of cloud streets is positively correlated with convergence, increased convective cloudiness in the cold dry air in this and the next stage may indicate deepening of the Low.

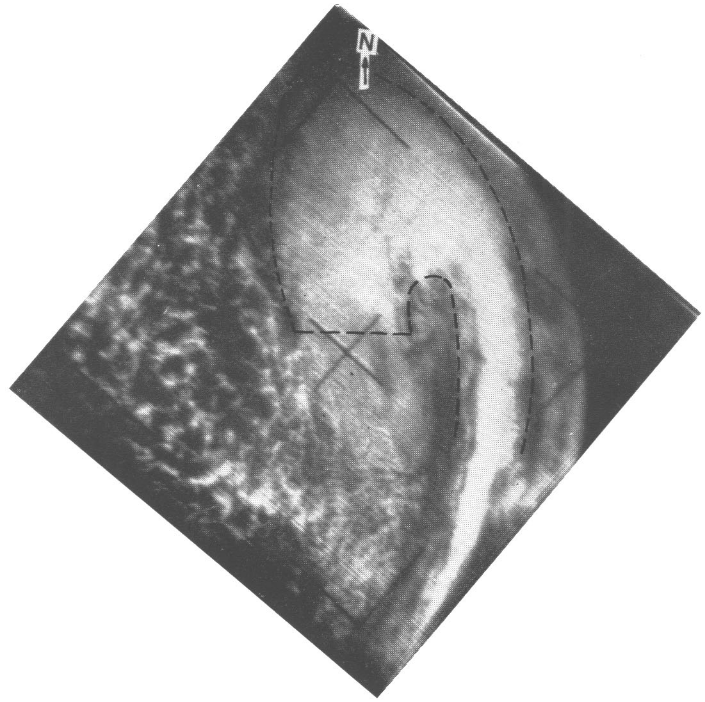

FIGURE 5.—Example of crescent-shaped cloud patterns found associated with 500-mb. troughs. Note U-shaped lower-level clouds, near center fiducial, which appear to identify surface pressure center. (TIROS VI wide-angle photograph; near 42°N., 173°E.; 0002 GMT, Nov. 14, 1962.) (From Rogers [3].)

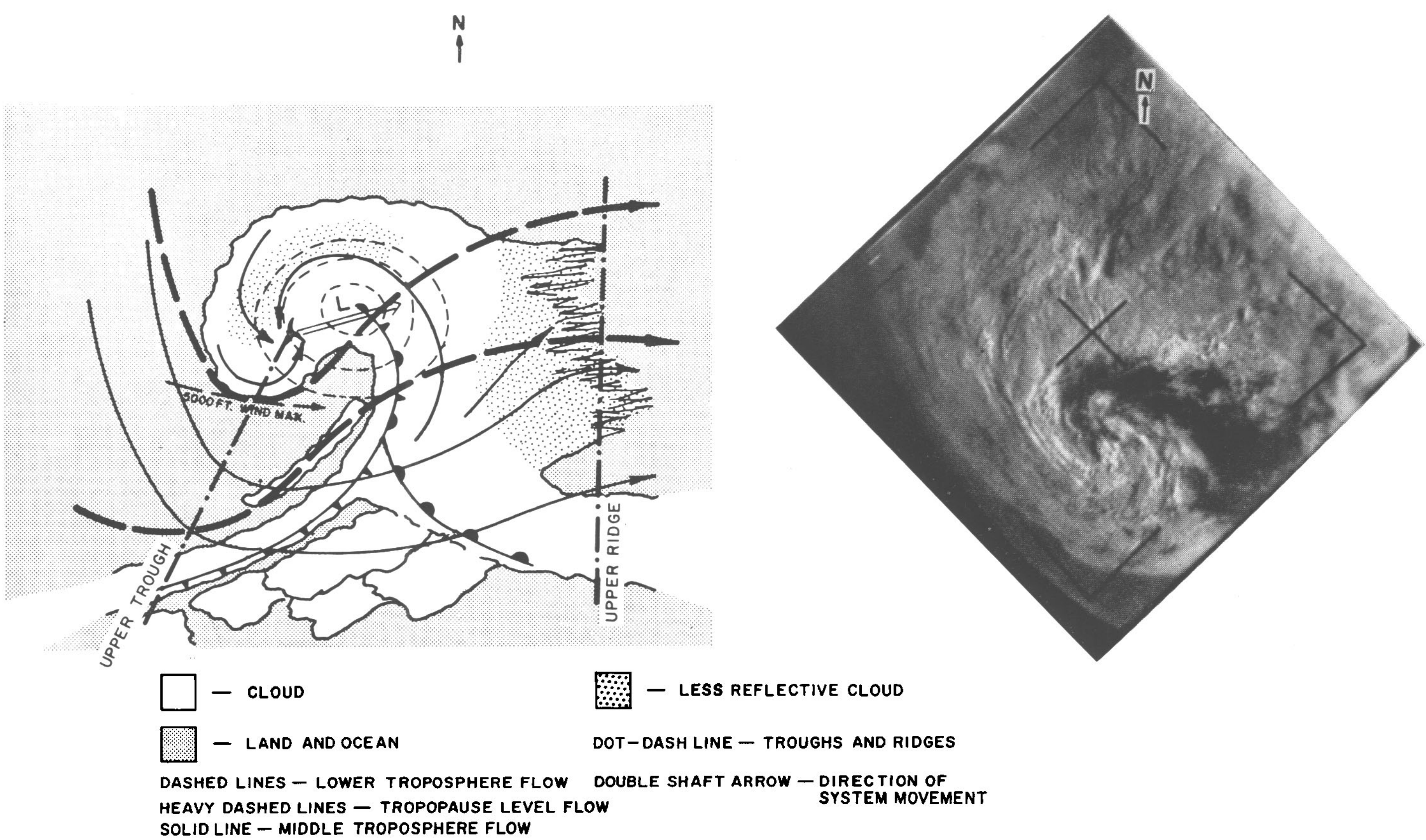

FIGURE 6.—Occluding cyclone, clear cold air (TIROS V wide-angle photograph; near 50°N., 80°W.; 1218 GMT, Sept 11, 1962).

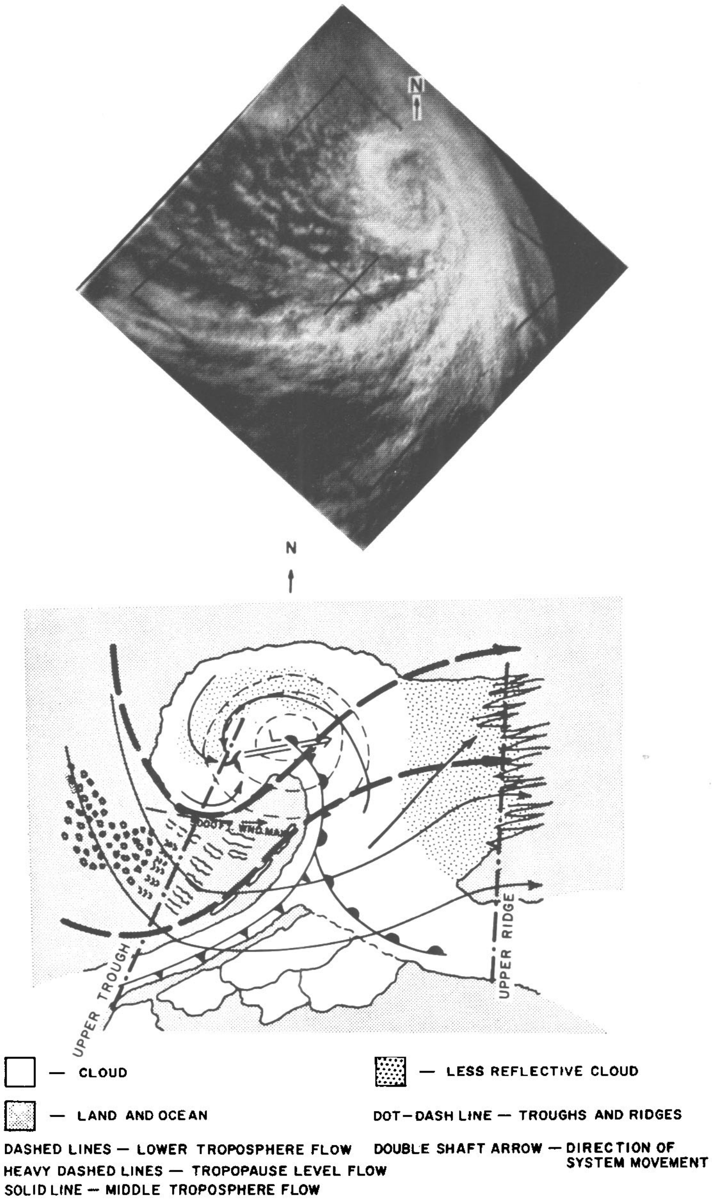

FIGURE 7.—Occluding cyclone, convective clouds in cold air (TIROS VI wide-angle photograph; near 46°N., 165°W.; 1307 GMT, Feb. 23, 1963).

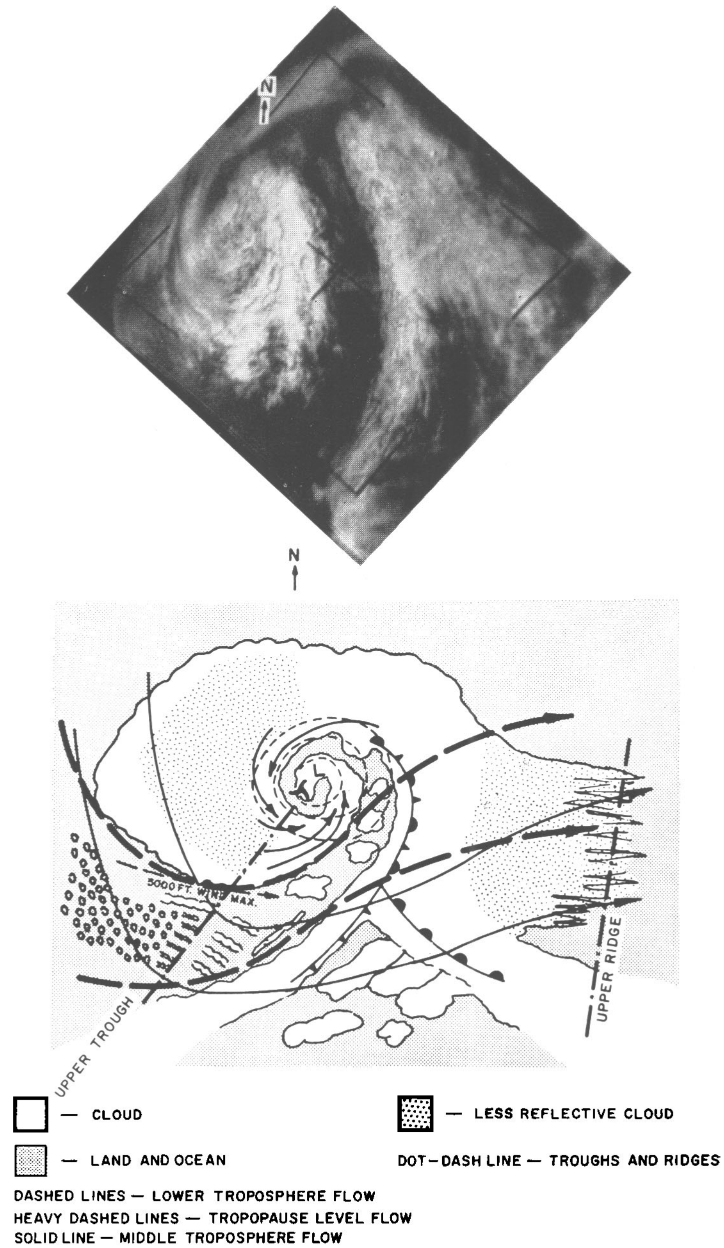

FIGURE 8.—Occluded mature cyclone, just prior to fullest maturity (TIROS V wide-angle photograph; near 56°N., 75°W.; 1250 GMT, Sept. 7, 1962).

FULLY OCCLUDED, MATURE STAGE

In this stage, there may be virtue in considering two substages. In the first, prior to fullest maturity, the dry air continues to spiral in about the vortex, reaching a stage of one or more complete revolutions about the center (fig. 8). In the second, the warm moist air, and the clouds in it, first connect across the cold air, cutting off that inside from any further supply, and the beginnings of dissipation are at hand (fig. 9). In the schematic of figure 9, the point of cut-off is just west of where the northern tropopause level flow line crosses the front; contrast this with the same area in figure 8.

Accordingly, as suggested by Rutherford [21], the degree of maturity is broadly shown by the increasing concentricity of the spiral bands and by a decreasing width of the clear air channel between them. The length of time provided for development, prior to the closing off of the dry air, has been suggested by Leese [13] as indicative of the depth achieved at the center of the Low. Sherr [3] found these mature vortices to have average departures from the seasonal and geographic normal of 15.6 mb. at the surface, and 581 ft. at 500 mb. The average 500-mb. departure at this stage was the greatest observed.

Particularly during this and the remaining final stages

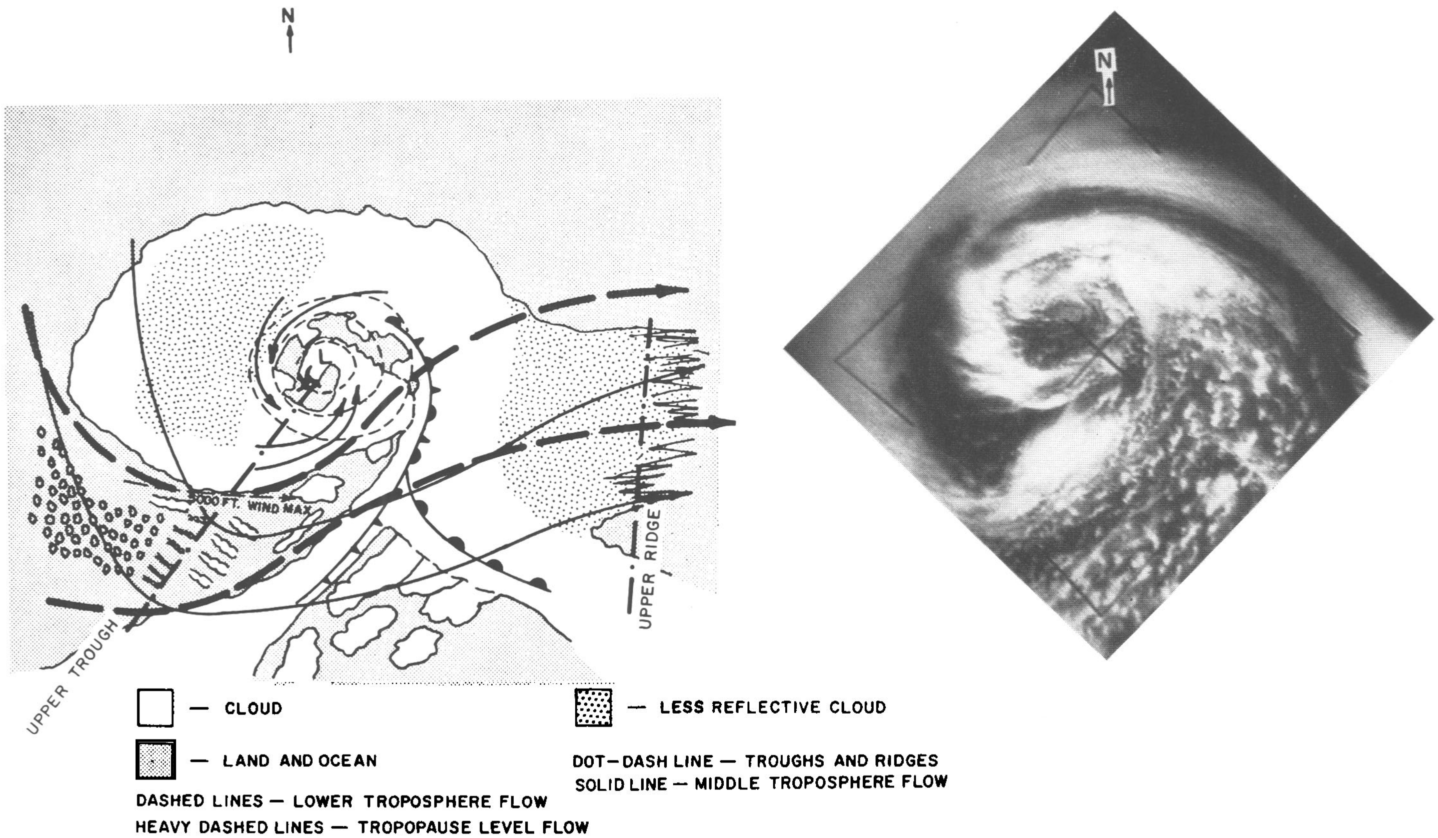

FIGURE 9.—Occluded mature cyclone, with dissipation about to start (TIROS V wide-angle photograph; near 57°N., 30°W.; 1305 GMT, Sept. 1, 1962).

of the system, pattern changes are slow. Glaser [8] has reported that patterns in Lows often last 24 hr. and so permit the Low to be recognized and identified from one day to the next. Serebreny et al. [23] state: "In general, broad-scale changes in clouds occur only through a major development in the synoptic situation. Cloud systems were recognizable for as many as four days, particularly in the middle latitudes."

At this stage secondary vortices have in several cases been noted to the west of the primary circulation. Winston and Tourville [28] describe this secondary spiral (visible in their fig. 2 and 3 and marked as G) as probably the remains in the mid-troposphere of an older system; they state it may still have been an effective circulation. The later studies of Rogers [3] suggest, however, that this secondary spiral was in all probability a nascent circulation rather than a dissipating system. Nagle and Serebreny [18] have noted a somewhat similar cloud vortex which appeared as a new development at least 24 hr. prior to any indication in the synoptic data and later produced significant precipitation. Rogers [3] found these cumuliform and cirriform vortex patterns in the polar air flow behind major cyclones to be indicative of a 500-mb. short-wave trough and a distinct surface trough. An example is shown in figure 10. The secondary is the small but still significant vortex between the center and eastern *fiducials; the primary* is outside the field of view, with its center over 600 n. mi. to the northeast of the secondary. These disturbances often develop into systems producing weather of considerable operational significance. Merritt [16] has discussed other cases of mesoscale vortices which were observed in several areas of the Southern Hemisphere and states that "the most interesting cases occurred near the edge of the (Antarctic) pack ice."

THE DYING STAGE

In this final stage, while organization is still apparent, there is some considerable variety to the configurations. The key factor seems to be the continued cut-off of the interior cold and dry air by a surrounding ring of warm, cloud-filled air (fig. 11). Rutherford [21] describes this as a ring cloud with an almost clear center, corresponding to a cut-off cold Low. Serebreny et al. [23] state: "In frontless vortices (cold cut-off cyclones) cloudiness is prevalent around the periphery of the vortex." Boucher and Newcomb illustrate examples in their figure 8; one of their cases is that discussed in more detail by Jones [11]. Another case of this stage has been studied by Fritz [7].

It is probable that the appearance is similar for both a major tropical vortex which has moved into temperate latitudes before decaying (the case studied by Jones seems to have been at least partly of this nature) and a purely extratropical cold-core system.

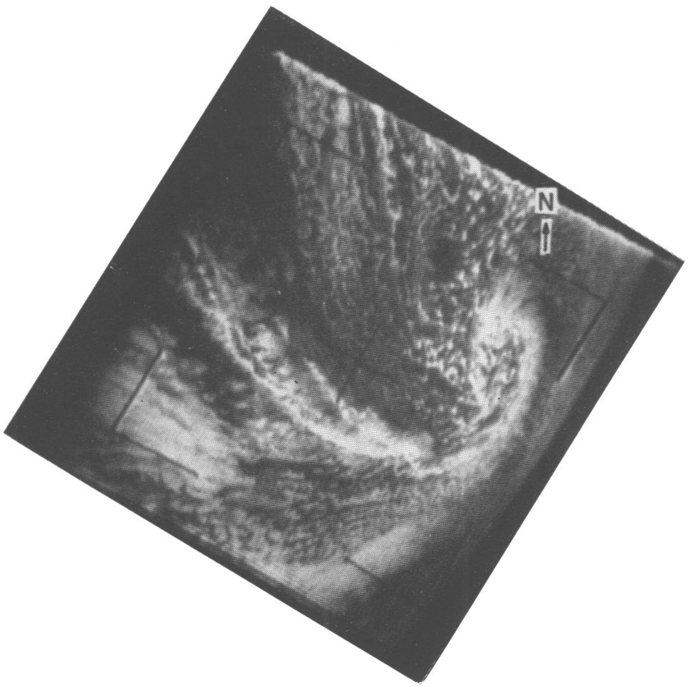

FIGURE 10.—Example of a vortex pattern in the polar air flow behind a major cyclone, indicative of a 500-mb. short-wave trough and a distinct surface trough. (TIROS VI medium-angle photograph; near 45°N., 155°W.; 2333 GMT, Nov. 10, 1962.) (From Rogers [3].)

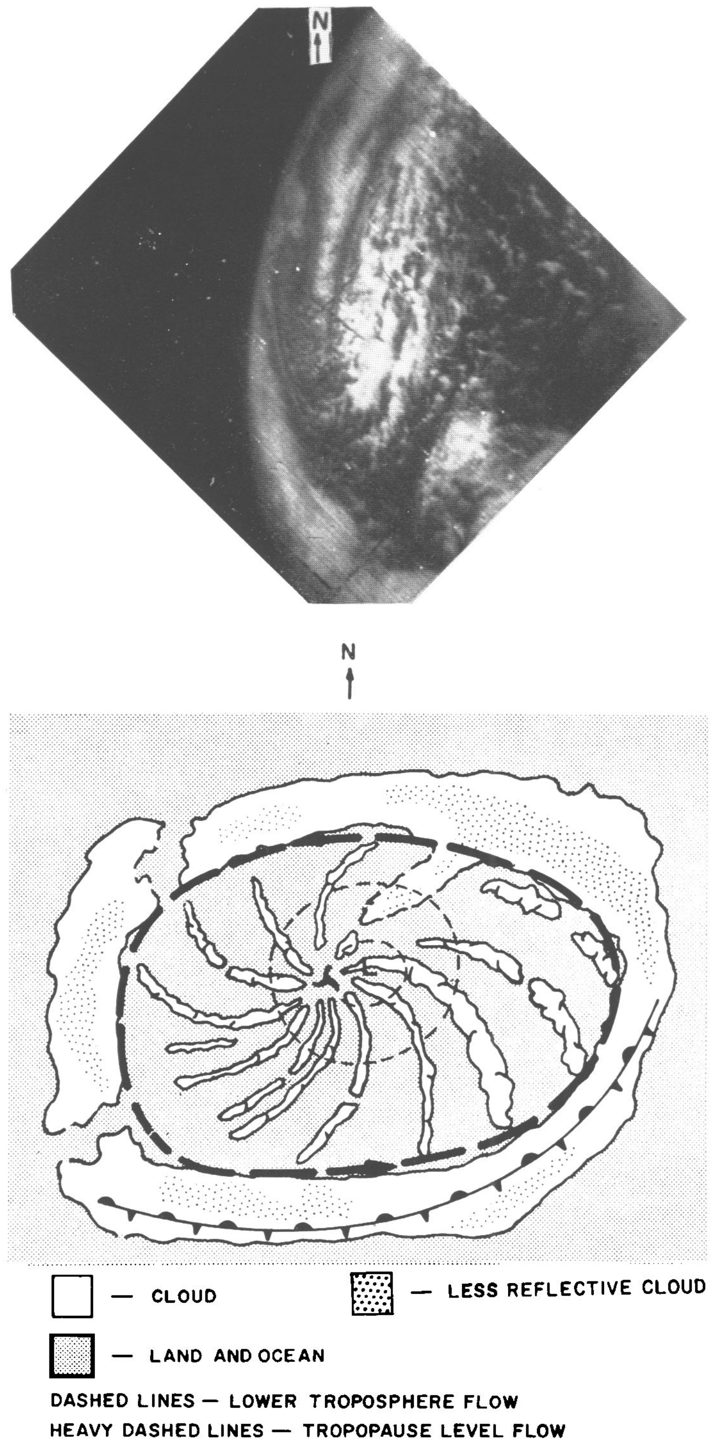

FIGURE 11.—Decaying cyclone (TIROS I wide-angle photograph; near 50°N., 20°W.; 1250 GMT, April 2, 1960).

Boucher and Newcomb [2] state that, in the decaying vortex, the number of cloud bands and their width, spacing, and character vary with the underlying surface, season, time of day, and circulation intensity. Jones [11] found that, as the vortex decays, the number of bands decreases and the cloud cover at the crest or center of the vortex becomes more broken. Glaser [8] also reports decrease in cloud cover and increase in the space between bands as indicating system weakening in this final stage.

Serebreny et al. [23] report the clouds and their patterns persist in the dying vortex after all indications in the synoptic data are lost. Boucher and Newcomb [2] indicate that in the final stages the vortex pattern may appear more intense than other observations suggest. It would thus appear that the clouds are a far more sensitive indicator of atmospheric activity than other types of data, detecting the earliest stages of cyclogenesis prior to other evidence (as discussed in relation to the frontal wave stage) and showing the persistence of a low-intensity circulation after it has otherwise become unapparent. For the analyst, this persistence indicates a need for caution to avoid forecasting more severe circulation, wind, and weather conditions in the final stages than may actually be present.

In his study, Fritz [7] noted an intrusion of a band of moist, cloud-filled air from the perimeter into (or over) the cut-off cold air. While he did not follow the further course of the storm, pictures and maps for the next day as published by Widger [26] suggest that while the outer periphery of the storm and circulation continued to decay, the central portion appeared to have maintained its intensity. The TIROS picture for the next day (TIROS I, orbital pass 29, Camera 2, Tape, Frame 18) shows the vortex apparently covering a smaller area, but now with a continuous spiral cloud band more suggestive of the mature than the dying stage. One is led to speculate as to whether such a warm air intrusion into the center of a cut-off cold core vortex might act in some sense like an internal warm frontogenesis, causing some degree of reintensification, or at least a temporary cessation of system degradation.

Serebreny et al. [23] report: "During the development of the cold cyclone downstream of the blocking ridge, the cutting off of the cold air supply seems to be marked in the satellite photographs by an extension of an amorphous cloud sheet around the northern perimeter of the vortex. The interior of the cut-off cold cyclone remains rather free of clouds during the development. While there is some evidence that major cloud systems spiral into these frontless storms, this characteristic is much more ill-defined than in frontal cyclones." It seems possible that the spiraling in of major cloud systems referred to by Serebreny may be another description of the moist, cloudy intrusion noted by Fritz.

Merritt [16] has noted that in cut-off cyclones "The low-level vortices are usually characterized by a banded cumuliform appearance while those in the upper troposphere are fibrous stratiform", as illustrated in figures 11 and 12.

Sherr [3] found dying stage vortices to have average departures from the seasonal and geographic normals of 12. 4 mb. at the surface, and 412 ft. at 500 mb.

3. VORTEX POSITION AND MOTION

LOCATION RELATIVE TO SYNOPTIC DATA

Boucher and Newcomb [2] indicate that the cloud vortex center tends to be west and/or equatorward of the surface Low, following the track of the surface Low but lagging behind its positions by about 12 hr. Coincidence of position between the cloud vortex and the 500-mb. Low seems to be somewhat better. Glaser [8] puts the typical cloud vortex position over the 500-mb. Low, equatorward and west of the surface pressure minimum but over the circulation center of the surface winds.

In a case studied by Hubert [9], the cloud vortex center was found to be west of the streamline vortex center at all levels from the surface to 500 mb.

Van Dijk and Rutherford [25] have suggested that when two circulation centers are discernible during the cut-off stage, they may correspond to the pressure centers at different levels.

Sherr [3] found the following relationships between vortex and pressure center positions:

Beginning of Occlusion Stage: More frequently related to a surface than to a 500-mb. Low, with the cloud vortex west and equatorward of the surface low.

Occluding Cyclone Stage: Nearly always within 200 mi. of a surface Low, and usually also within 200 mi. of a 500-mb. Low. While the surface Low positions tend to scatter about the cloud vortex, the 500-mb. Lows are usually located north or east of a northwest-southeast line passing through the position of the cloud vortex.

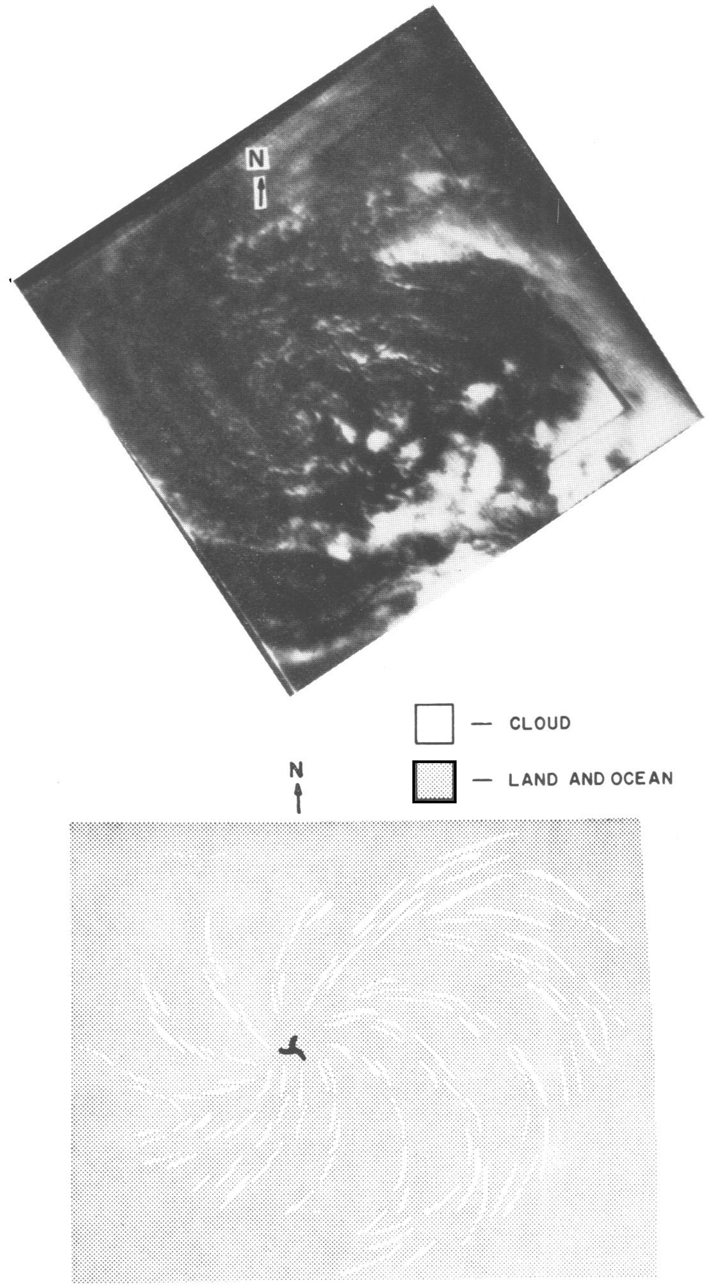

FIGURE 12.—Upper-level, cut-off, decaying cyclone (TIROS V wide-angle photograph; near 24°N., 44°W.; 1447 GMT, Dec. 12, 1962).

Fully Occluded Cyclone: The cloud vortex is usually within 200 mi. of both a surface and a 500-mb. Low. The surface Low has some tendency to be northeast of the cloud vortex, with the 500-mb. Low slightly displaced to the south of the surface Low position.

Dying Cyclone: The related surface and 500-mb. Lows are usually found to the east of a north-south line through the cloud vortex center.

As shown in figure 13, Sherr found the one-standard-deviation circle for the differences between the positions of cloud vortices and related surface pressure centers

729-085—64——2

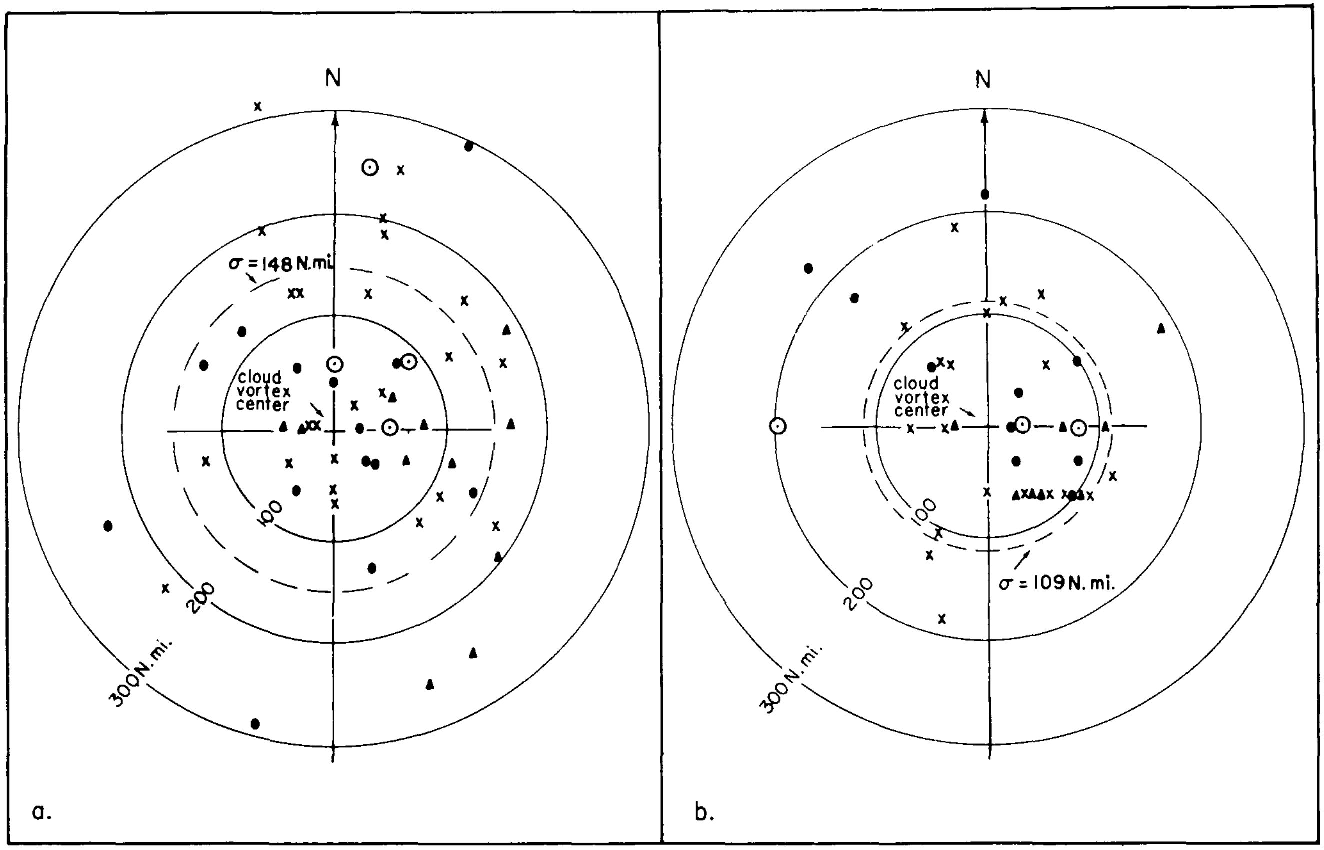

FIGURE 13.—Relative positions of cloud vortices and related (a) surface pressure centers, (b) 500-mb. centers. (From Sherr [3].) Solid circle=occluding cyclone, circled dot=beginning of occlusion, x=fully occluded cyclone, triangle=dying cyclone.

to have a radius of 148 n. mi. For related 500-mb. centers, the radius of the corresponding deviation circle was 109 n. mi. As Sherr [3] points out, inadequate conventional data and consequent inaccurate standard analyses are probably significant contributors to the magnitudes of these values.

Since a clearly definitive cloud vortex seems to require the existence of an upper-air circulation, better correspondence between the cloud vortex and upper-air vortex or trough (as compared to the surface center) seems reasonable in the more mature stages.

ALTITUDE

As mentioned above, Merritt [16] has found low-level isolated vortices to be characterized by a banded cumuliform appearance while those in the upper troposphere tend to be banded stratiform. He also indicates that the relative cloud ". . . brightness gives some indication of the vertical extent of [any] vortex since brightness is usually positively correlated with the thickness of the clouds."

Sadler [22] reports that, in the Tropics, it may be difficult to distinguish from the cloud pictures alone between low-level warm vortices and those restricted to the upper troughs. He suggests: ". . . the satellite photographs are not sufficient within themselves but must be used in conjunction with the proper tropical synoptic charts and a knowledge of the regional climatology."

MOTION

Merritt [16] has studied the motion of approximately 15 examples of Southern Hemisphere vortices which could be observed on two or more days. ". . . the assumption was made that the future motion of the vortex system was governed by a 'steering current' which could be determined from the cloud patterns using techniques . . ." which will be summarized in the later discussion of winds.

"The results of this limited sample show a useful relationship between the orientation of the major cloud band and the direction of motion of the vortex system for the following 24 hours. Successful application of these results is extremely dependent on the correct estimation of the intensity of the vortex system, and on evaluation of the steering current. The steps required are listed below:

"a) If the vortex is in the pre-occlusion [fig. 3] or early occluded [figs. 4, 6, 7] state of the Boucher-Newcomb model, the vortex system will move parallel to a direction obtained by averaging the orientation of the [frontal cloud] band starting at its eastward limit and continuing westward until 10° west of the vortex center. The use of this averaging of segments which subtend approximately a 30° angle, measured from the vortex center, is recommended.

"b) If the vortex is in the fully occluded stage the expected motion (in the southern hemisphere) will be parallel to the general orientation of the major cloud band.

"In some examples of the pre-occlusion stage, the direction of future motion was indicated by the orientation of the isolated thin bright band which . . ." was located in the cold air west of the poleward bulge of cloudiness and between the center of the bulge and frontal cloud band. This band, illustrated in figure 3, often seemed to parallel the jet stream.

4. FRONTAL POSITIONS

WARM FRONT

In the papers reviewed, there was little or no discussion of the position of the warm front relative to the vortex cloud patterns. By implication, it would be expected to be east of the vortex center. Seldom does there appear to be a clearly discernible boundary between the convective cloudiness in the warm air and the more stratiform cloudiness due to overrunning poleward of the surface warm sector. Accordingly, there seems presently to be little guidance for proper placement of the warm front within the cloudiness east of the vortex. Since, even with good synoptic observations, placement of the warm front is still often a problem, this ambiguity is not unexpected. The evidence shows that the classical concept of overrunning warm air is of secondary importance to the large-scale lifting associated with the dynamics of the cyclone. Radar and detailed synoptic studies have substantiated this position and it would be surprising to find anything different from satellite information.

COLD AND OCCLUDED FRONTS—FRONTAL WAVE TO BEGINNING OF OCCLUSION STAGES

During this phase, it seems probable that there is a tendency for the bulk of the frontal cloudiness to be west and poleward of the front. East and equatorward of the front, conditions tend to be clear to broken convective cloudiness, but this warm sector convective cloudiness tends to become heavier east of the front as the vortex intensifies and one or more squall lines form. Such convective cloudiness usually tends to have some breaks in it. Conditions along these lines were noted by Timchalk and Hubert [24].

Serebreny et al. [23] state: "When the cloud system lags behind the front, the upper winds are apt to be parallel to the front, at least as far as the clouds extend." This seems compatible with wind flow-frontal orientation patterns to be anticipated during the early stages of development.

COLD AND OCCLUDED FRONTS—OCCLUDED STAGES

At these stages, the frontal band generally seems to have become much narrower, usually with comparatively definite breaking or clearing immediately to its rear. *Extensive* cloudiness of a more or less broken convective nature is usually found to the east of the frontal band in the warm sector. At times, this convective area may take the form of a second band, east of and parallel to the frontal band, with a clear area or one of lesser cloudiness separating the frontal and convective bands. The convective band is associated with a squall or instability line.

Bristor and Ruzecki [4] discuss two parallel bright bands along or parallel to the front, with the easternmost probably a squall line under the moist tongue. They believe the surface position of the front is probably along the eastern edge of the western cloud band, with the band of clouds to the west and the clearer (until the squall line convective cloudiness is reached) warm air to the east. In their studies, both Winston [27] and Winston and Tourville [28] also place the front at the eastern edge of the major (or more western) cloud band. Boucher and Newcomb [2] place the front under the solid cloud band ahead of the western clear area and parallel to its edge. Considering the comparative narrowness of the frontal band frequently observed in these stages, this does not seem a significant disagreement with the other findings just above. Serebreny et al. [23] state: "When the cloud mass lies ahead of the cold front with a sharp edge to the cloud system at the frontal boundary (rapid clearing), then the winds aloft are usually normal to the front." Such a frontal-winds-aloft configuration would be more common in these occluded stages; the cloud mass they speak of would be the convective cloudiness in the warm air ahead of the front, with a narrow and sharp frontal band behind.

Rutherford [21] states there may be an instability line ahead of the frontal band; Van Dijk and Rutherford [25] indicate it may be differentiated from the frontal band by the scalloped edges to the clouds.

In the decaying stages of the cyclone, with the frontal band less obvious, Jones [11] suggests it may lie between the spiral bands to the west and an area of broken to overcast conditions to the east of the vortex, presumably the remains of the convective cloud-instability line area. In these decaying vortices, Boucher and Newcomb [2] suggest the spiral bands west of the main frontal band or position may be the weather producers that have led to the frequent insertion in analyses of secondary cold fronts.

Boucher and Newcomb [2] indicate the frontal slope can be deduced from the width of the frontal cloud band, while Rutherford [21] amplifies this by placing the western edge of the frontal band about coincident with the 500-mb. trough line. This, of course, suggests that the front becomes more vertical as the cyclone develops, which is to be expected as the 500-mb. Low moves over the surface Low and the cold core cyclone itself becomes essentially vertical.

At least the remnants of the front can be found in the satellite photographs after it has moved well into the Tropics. Serebreny et al. [23] state: "The extensive cloud bands in the lower latitudes indicate that the effects of the penetrations of cold air from the north are quite long-lasting—even after the means to detect fronts on the conventional basis have been lost." "On occasion the extent of this band can be followed westward to the frontal system lying to the west of the anti-cyclone."

5. AIR MASSES

The satellite pictures of the cloud vortex patterns associated with cyclonic development indicate that two air masses are primarily involved:

1. The warm and typically moist tropical air which flows poleward ahead of the cold front. At least during the stages of active cyclonic development, this flow often seems to split just east of the center of circulation. One tongue curves westward and eventually equatorward over and to the rear of the cyclone center. The other curves eastward and corresponds to the ascending warm air flow over the warm front. Corresponding to this warm air flow are the convective cloudiness and instability lines ahead of the cold front, the major cloud bands and/or cloud mass that circle the vortex center, and the just previously mentioned warm frontal cloud deck. As has been noted by Glaser [8], Bristor and Ruzecki [4], Oliver [19], and Fritz [7], these cloud patterns closely resemble, and so probably depict, the moist tongue configurations commonly noted in isentropic analysis.
2. The dry and typically cold air which moves into the storm from the west and poleward, curves equatorward of the circulation center, and spirals into it behind the cold front. This clear or clearer area (often it is substantially filled with cellular convective cloudiness) closely corresponds to an isentropic dry tongue, as noted by Glaser [8] and Oliver [19].

In the mature and decaying cyclone, the cold dry air is cut off, lying in the center of the storm surrounded by the warmer moist air (fig. 11).

THE COLD DRY AIR

The cold, "dry" mass seems to have been given the most attention in studies to date. This may result from two reasons: (1) such relatively clear areas were not expected to be so frequent in major cyclones and so aroused considerable interest; and (2) the convective and other cloud masses, patterns, and orientations within this air can be readily discerned, encouraging study.

As Boucher and Newcomb [2] have pointed out, the degree of clearness or partial cloudiness in this air mass, sometimes referred to as the "clear" zone, is related to such parameters as humidity and the extent of subsidence. Serebreny et al. [23] point out that the post-frontal cloud cover is governed by the thermal state of the cold air and the length of its trajectory. Bristor and Ruzecki [4] suggest these dark clear areas are indicators of dry air when the presence of clouds would otherwise be expected. Leese [13] indicates this air mass has a tendency to be clear over land and more filled with convective clouds over the oceans. Fritz [7] indicates that, within this air mass, the brighter clouds mark the areas of less stable air, as compared to those portions where the clouds appear grayer. Serebreny et al. [23] state: "Post-frontal regions, in which fresh, cold air is involved, are observed in satellite photographs as areas covered by small, cellular type clouds, often in streets but not necessarily so."

Most of the investigators consider the clear area as indicative of subsidence. Rutherford [21] states it corresponds to subsiding air west of the trough. Timchalk and Hubert [24] find both subsidence and the dry air equatorward of the low-level wind maximum. Leese [13], however, ascribes the clear area to advection and not to direct subsidence. He finds slight upward velocities, at the 600–700-mb. level,[2] in the dry air that has entered the vortex, and believes the drying, clearing subsidence took place farther west, before the air entered the vortex. Deardorff [6] finds "a region of subsidence or clearing extending westward from the vortex center."

At the boundaries of the clear area, Bristor and Ruzecki [4] suggest that, at the eastern boundary just behind the front, scattered cloud lines near the front may be clouds in the warm air above the front, with the last faint patches marking the leading edge of deep cold air. The equatorward and westerly sharp edges of the clouds around the vortex, west and equatorward of the vortex, may be the poleward and easterly edge of the area of descending motion. Of course, how well these boundaries can be seen will be dependent on the extent and location of convective cellular cloudiness in the dry air.

THE MOIST WARM AIR

Less attention appears to have been paid to the warm moist air, particularly within the vortex proper. This may result from two causes: (1) in many cases, the bright cloud areas have insufficient contrast for any detail to be detected within this cloud mass, and (2) the amount of concurrent conventional data in the upper levels coincident with the cloud tops is less than at the surface, making comparative analyses more difficult. Further complicating the second point is the uncertainty that often exists as to the altitude of the visible cloud tops.

Bristor and Ruzecki [4] and Fritz [7] suggest the cloud mass areas within the vortex, west and poleward of the clear area, probably result from ascending motion of the moist warm air more or less along isentropic surfaces. Fritz has noted that, accordingly, one would expect the cloud top altitudes in these areas to decrease toward the pole. Deardorff [6] states: "Penetration of [the] region of subsidence by clouds advected [equatorward] from the region of upward motion just [poleward] of the center is suggested from the figures and seems plausible."

It would seem that specific attention to these warm, moist, cloud mass areas might be fruitful. To have a reasonable chance of producing useful results, study should be concentrated on storms over areas with plentiful concurrent upper-air data, and on cases showing good con-

[2] The small values Leese obtains, and the lack of calculation for more than one level, suggest caution in the use of these findings until further corroborated.

trast and adequate pattern detail within the overall cloud mass. In this last connection, the slightly amplified contrast and consequent detail provided by LogEtronic processing might be helpful.

THE MATURE AND DECAYING CYCLONE

As Fritz [7] indicates, in the mature cyclone the stratiform clouds surrounding the storm mark a warm moist tongue which has encircled the storm center, which is now filled with cold, dry air. The stratiform cloud areas appear associated with upward motion. There may be upper-level descending motion even over the cumuliform cloud masses in the center (fig. 11).

Nagle and Serebreny [18] have noted that in these stages the absence of cellular clouds in recirculated Arctic air can be taken as an indication of modification of such an air mass.

Serebreny et al. [23] indicate the clouds and cloud patterns persist after all other synoptic indications of the decayed vortex appear to be lost.

HUMIDITY NEAR THE SURFACE

Timchalk and Hubert [24] found that, in general, the surface relative humidity patterns were well correlated with the distribution of low clouds, but that in some regions stability considerations prevented low cloud formation in spite of adequate humidity.

AIR MASSES AS RELATED TO THE CLASSICAL FRONTAL-WAVE MODEL

Serebreny et al. [23] in their study of the May 20, 1960, Pacific case (see also Oliver [19]) found an excellent correspondence between the observed cloud patterns and other synoptic observations, and the classical frontal-wave model. They state:

"In regard to the cloud distribution over a wide area, Bergeron [1] has presented a schematic model of the relation of clouds, fronts, and jet streams within a wave system. His assessment of the cloud distribution is strongly supported in the first part of this case history. In fact, the mosaic [Also discussed by Oliver [19].] of the 20th of May [1960] is almost classical in terms of his model. Bergeron's model of weather regions . . . [is shown in fig. 14]. Essentially, this model contains eight weather regions related to the principal fronts and air masses." [Petterssen [20] gives a fuller description of these weather regions.]

"The satellite photographs for the first four days during which zonal flow predominated provide confirmation of the concept of the distribution of clouds with the polar-front, as exemplified by the cloud distributions in Bergeron's model.

". . . it was observed that a high degree of moisture through a deep layer is carried ahead of the cold fronts, with pronounced subsidence and drying within the front itself above about the 600-mb. level. The post-frontal area is characterized by a moderate degree of moisture in a deep layer, coupled with marked upward velocities. This translates into a satellite photograph of small cellular clouds. Warm fronts show marked subsidence in and ahead of the frontal surface, with most of the moisture lying on the warm side of the frontal surface.

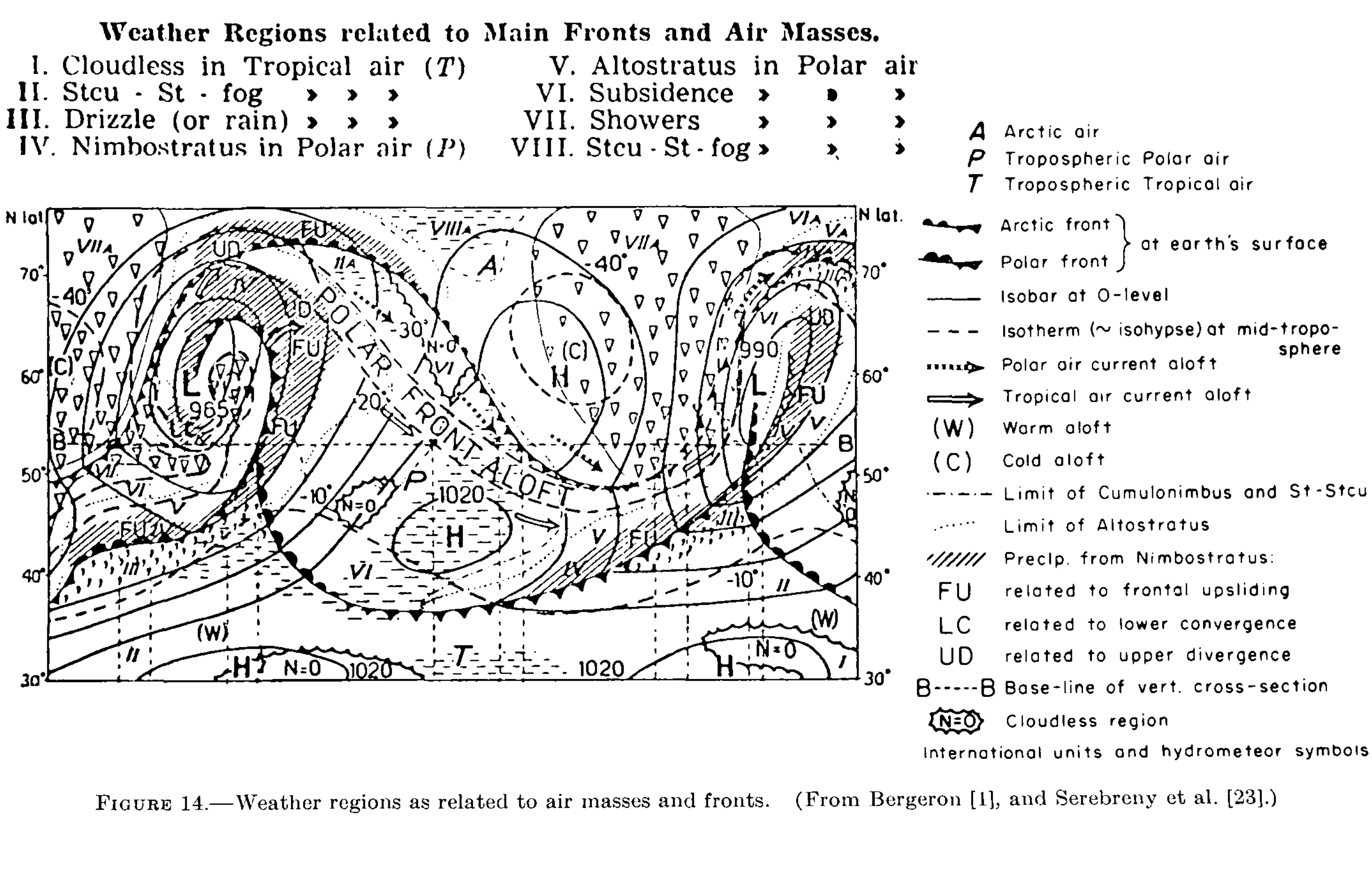

FIGURE 14.—Weather regions as related to air masses and fronts. (From Bergeron [1], and Serebreny et al. [23].)

"A comparison with other studies indicated that the distribution of moisture and vertical velocities were [*sic*] quite similar, leading to the conclusion that these distributions are perhaps typical of deep troughs with fronts and strong ridge conditions. Satellite photographs taken from additional cases in the TIROS catalogue during similar synoptic conditions will show if the pattern and type changes in cloud cover are also comparable."

6. WINDS

The relationships between wind direction (let alone speed) and cloud patterns, lines, streets, bands, etc., are, at best, complex. Varied indications showing cloud orientations both parallel and perpendicular to the wind flow, as well as parallel to the wind shear vector, have been obtained in the studies of satellite cloud pictures. It is probable that considerable time, study, and effort remain before anything approaching unambiguous results is at hand.

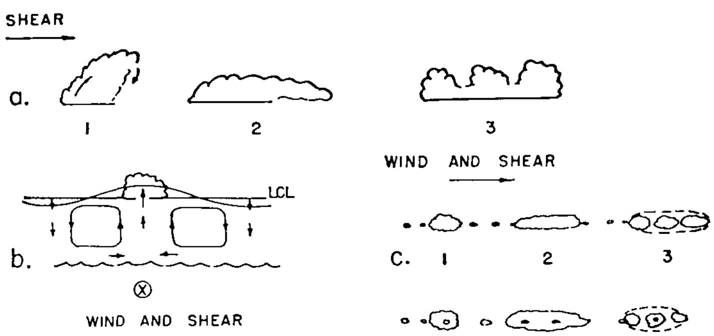

Figure 15.—Reproduction of figure 10 from Malkus [15]. "Schematic illustration of the hypothesis regarding the formation of rows of cumuli when the low-level wind and the shear in the lower cloud layer lie in the same plane. *a* The effect of shear in three stages: (1) Little growing cloud tilts downshear, and (2) lies down downshear as updraft dies; (3) new little cloud grows from the prostrate body. *b* The effect of Avsec rolls, wind, and shear at right angles to plane of diagram (blowing into the paper). The wavy line denotes the top of the mixed layer, raised in zones where the roll motion is convergent and upward, depressed where the roll motion is divergent and downward. Cloudlets break out where the mixed layer reaches condensation level—that is, at roll crests. *c* Combination of the direct shear effect in *a* and the Avsec rolls in *b* produces cumulus rows parallel to the flow, which elongate downshear."

Some light would appear to have been shed on the basic sources of these difficulties by the studies of Malkus [15], and an understanding and utilization of the principles of her findings may assist in the deduction of wind direction from cloud patterns in those cases in which the nature of the cloud pattern being examined is available from the information in the picture. In any event, her findings give a better idea than may previously have been available on the nature and extent of the ambiguities inherent in wind direction deductions using cloud patterns.

Malkus shows that: "When there is a single shear between a cloud layer moving fairly uniformly and its lower boundary, the parallel mode develops by a simple superposition of Avsec rolls and individual clouds leaning downshear." Her illustrations of this mode of formation and an example of it are reproduced in figures 15 and 16. "When there is wind-turning within the cloud layer, the individual clouds lean across the rows, which may then be several clouds wide." Malkus' illustrations of a case of this "parallel mode with rows several clouds wide" and the mode of formation are reproduced in figures 17 and 18.

She further shows that: "A marked shearing imposed aloft upon the convective layer brings in the cross-wind mode, oriented with the upper shear. It may be superposed on the parallel mode to make a checkerboard, or in extreme instances it may appear alone, so that the only cloud rows are at a high angle to the wind." She shows two striking examples, reproduced in figure 19. ". . . cumuli (*cu*) line up in the direction of the low-level wind; the cross-wind rows line up along the shear vector between the low-level wind and the wind above the shear layer; anvils line up along the shear vector between the low-level wind and the wind at anvil level." "The 40- to 50-mile (65- to 80-km.) spacing of the cross-wind mode . . . may be coincidental, or it may provide a clue to the dynamics of this mode that we do not yet know how to read. The

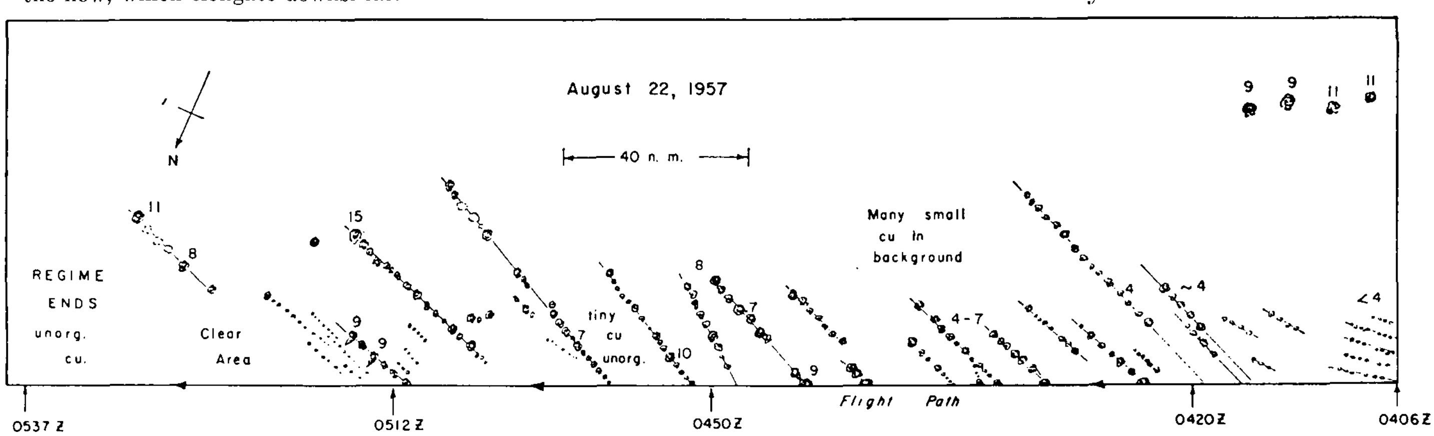

Figure 16.—Reproduction of figure 9a from Malkus [15]. "The simplest case of the parallel mode, with cloud rows one cloud wide, occurring when trade wind and vertical shear are in the same plane. . . . Cloud heights are in thousands of feet; when the height of an individual cloud is given, this cloud is generally the highest in its row." The surface winds were from the southeast, with no wind turning with height.

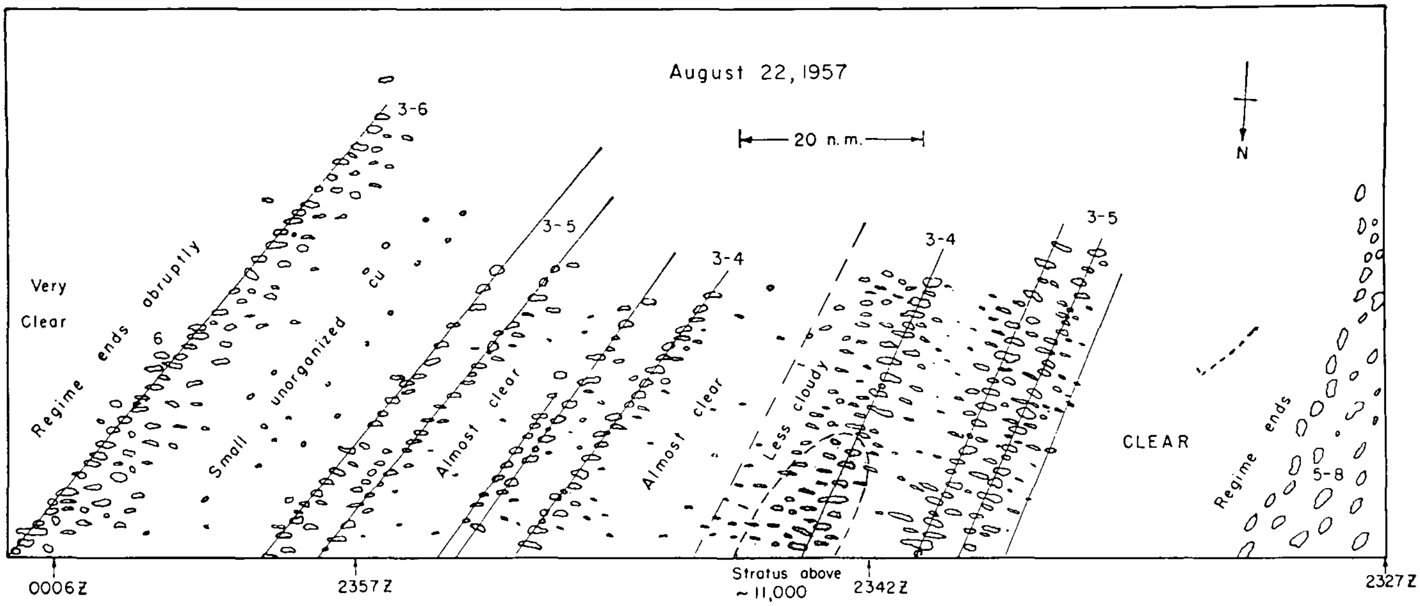

FIGURE 17.—Reproduction of figure 11a from Malkus [15]. "Parallel mode with rows several clouds wide, occurring when the trade wind and the vertical shear in the cloud layer are at a high angle to each other. . . . Not all the clouds photographed were included. The length and spacing of the rows are to scale. The height ranges are in thousands of feet. The shaded region denotes a patch of stratus above the cloud row." The surface wind was from the northeast at 0000 GMT.

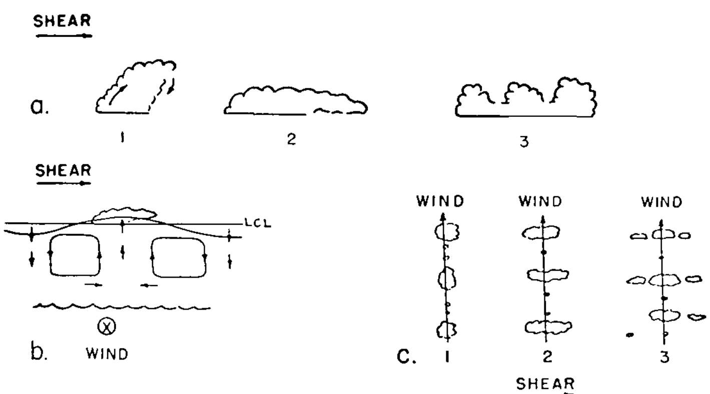

FIGURE 18.—Reproduction of figure 12 from Malkus [15]. "Schematic illustration of the hypothesis regarding the formation of rows of cumuli when the low-level wind and the shear in the lower cloud layer are at right angles to each other. *a* The effect of the shear elongates the cumuli downshear, as shown in Fig. 10a [fig 15a here]. *b* Avsec rolls lined parallel to the wind (which blows directly into the diagram) but at right angles to the shear (which points from left to right in the plane of the diagram). Cloud rows develop along the direction of the wind, as suggested in Fig. 10b [15b] but the iudividual clouds are elongated normal to the rows. *c* Combination of *a* and *b* showing the clouds stretched downshear normal to the Avsec rolls. The clouds are most likely to break out along the roll crests, but there is some spreading into the interstices."

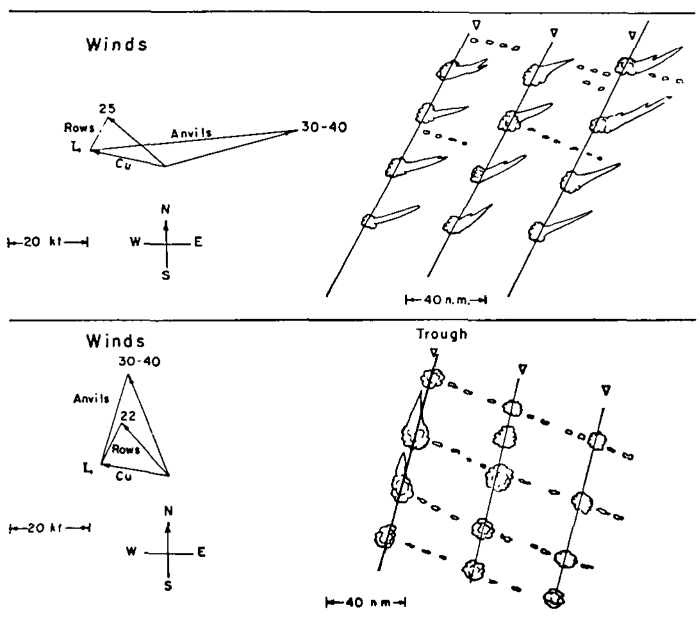

FIGURE 19.—Reproduction of figure 6 from Malkus [15]. "A schematic summary of cloud organization [in the presence of cross-wind shear]. Winds (in knots) are shown at left. *L*, low-level wind; arrows marked 25 and 22, respectively (for thousands of feet), winds above the shear layer; arrow marked 30–40, the mean wind for the 30,000- to 40,000-foot layer, or anvil region. Note that cumuli (*cu*) line up in the direction of the low-level wind; the cross-wind rows line up along the shear vector between the low-level wind and the wind above the shear layer; anvils line up along the shear vector between the low-level wind and the wind at anvil level."

factors that govern the relative degree of development of the two modes [parallel versus cross-wind] are still unspecified . . ."

A very significant problem from the viewpoint of the satellite meteorologist is that available camera resolution usually prevents seeing the individual, single cloud rows in the parallel mode. Accordingly, when an attempt is made to interpret the winds associated with those clouds that do appear arranged in rows, there is often little or no basis for determining whether they represent the cross-wind mode or the parallel mode with rows several clouds wide.

LOW-LEVEL WINDS

Various suggestions for deducing low-level winds from cloud patterns are scattered through the papers in the literature which are concerned with cloud vortices. Hubert [9] suggests that streaky cloud patterns, presumably parallel to the wind flow, may indicate higher wind speeds than in the case of parallel lines of cellular clouds. Madvig [14] indicates that cumulus cloud streets, generally parallel to the wind, are often found in the warm sector. Serebreny et al. [23] suggest that when the direction of the jet stream is known or can be deduced, cumulus cloud lines perpendicular to it may be indicative of strong low-level shear.

Winston and Tourville [28] found that in a storm just prior to the mature stage the major cloud bands were parallel to the surface and 700-mb. winds. Timchalk and Hubert [24] suggest that the "clear" air penetration into the cyclone may be due to a low-level jet of dry air and that, at about the occluding cyclone stage, the 5000-ft. wind maximum may lie about along the equatorward edge of the cloud mass which has been advected equatorward over the west of the center of the Low (figs. 6, 7, 8, 9).

Leese [13] states the rate of circulation about the vortex can be deduced from the rate of advection of the dry air spiraling in from the west and the rate of penetration of the cloud cover moving over and west of the center from a more or less poleward direction. It seems probable to the author that the dry air speed would be more representative of winds at intermediate levels, while the cloud mass movement would apply more to upper-level flows. Leese further suggests that, during the occluding stage, changes in the width of the spiral clear area can indicate changes in the speed of circulation about the Low; he states: "The spiral clear area in [such cases] is the result of an advective pattern made up in part by the movement of the Low-pressure area and also by a component of flow toward the center of the low. A decrease in either the speed of movement of the low or the inflow component would result in a more circular advective pattern, especially in the southeast quadrant. . . . A more circular advective pattern would in turn result in a decrease in the width of the spiral clear area. . . . [If] no change in the speed of movement of the low [can] be detected at the surface during [the] period and since it is reasonable to assume that no change in the speed of movement has occurred at any level over this time period in a system with a vertical slope . . . , it is concluded that the decrease in width of the spiral clear area can be attributed to a decrease in circulation around the low."

Wind Deductions From Cellular Cloud Patterns in the Cold Dry Air: The wind/cloud-pattern relationships in this area of the cyclone have been the subject of particularly intensive investigation. At least a general indication of the wind direction is deducible from the findings of Krueger and Fritz [12], Winston and Tourville [28], and Winston [27] that cellular cloud patterns in this portion of the storm occur with cold air flow over a warmer water surface at levels below 5000 ft.

Winston [27] found the major, non-frontal bands of these cellular clouds may be perpendicular to the surface and the 700-mb. flow. Leese [13] found that smaller cloud lines in the dry air under the inversion may also be perpendicular to the wind flow. Serebreny et al. [23] report: "Cloud streets in post-frontal regions are apt to lie at an angle or even perpendicular to the wind flow in . . ." lower to middle levels.

Rutherford [21] states that the cellular patterns are indicative of small vertical shear. Conover [5] and Madvig [14] both state: "The low-level winds generally blow at an angle of 45 degrees to the clouds and into the open end of crescents or cells. Since the speeds increase constantly with altitude, the wind shear is fairly small, but it is suspected to be somewhat higher for crescents than for polygonal cells."

The most thorough investigation of wind/cloud-pattern relationships in these cellular clouds has been made by Mr. C. W. C. Rogers of ARACON Geophysics Company and is reported by Merritt [16]. The following results are extracted from that source:

". . . laboratory experiments and . . . earlier atmospheric studies indicate that, in order to relate the cumuliform patterns to the low-level wind direction and speed, we need a cumuliform-producing layer which satisfies one of the following conditions:

a. No vertical shear.

b. Vertical shear parallel to the direction of the low-level wind.

"The second condition is likely to be satisfied when the convective cloud layer is sufficiently shallow to make significant changes in wind direction improbable.

"The cumuliform patterns in the regions to the rear of major cyclones are often constrained to the first few thousand feet above the surface by a low-level subsidence inversion through which they cannot penetrate. In such areas the low-level wind is usually parallel to the shear vector in the cloud layer. The cellular patterns studied by Krueger and Fritz [12] were located in such regions.

"From the TIROS V and VI photographs of the Southern Hemisphere during July, August, and September 1962, it was possible to obtain 21 cases in which a surface wind speed or direction could be related to a low-level cumuliform pattern. Based on these cases, the following wind velocity/cloud pattern categories were tentatively devised for determining wind speed and direction . . ." in areas of cumuliform cloudiness to the rear of major cyclones:

"A) Wind Speed 0–12 knots—Polygonal or Elliptical Chains

"1) At the low end of this wind speed range, the cumuliform pattern is composed of regular polygonal cells." "These provide no information about the wind direction. [fig. 20a].

"2) Toward the higher end of the speed range, the polygonal cells are distorted into ellipses which tend to line up in a chainlike pattern. The wind direction is parallel to the major axis of the ellipse chain. [fig. 20b].

"*B) Wind Speed 13–22 knots—Scalloped and Highly Elliptical*

"1) Chain-like cloud patterns with the crosswind links missing. [fig. 20c].

"2) Highly elliptical or oblong patterns. [fig. 20d].

"In both of these cloud pattern types, the wind is parallel to the longer dimension of the elements or groups of cloud elements.

"*C) Wind Speed 23–37 knots—"Blown-out" Ellipses and Rows*

"1) In the lower end of this wind speed range the pattern appears like "blown-out" ellipses which have an open end; the ellipses are no longer joined together in a chain. The wind is parallel to the major axis of the ellipse. [fig. 20e].

"2) In the upper speed ranges of this category, the pattern assumes the appearance of parallel rows of undefined cloud elements. These rows are not continuous, but rather are composed of short segments. The wind direction is parallel to the orientation of the rows." [fig. 20f].

Section 4.1.2.1.1 (pages 20–26) of [16] provides illustrative case examples of these relationships. The report also states: "While the categories described . . . represent the patterns observed in the majority of the cases examined, there were variations which are significant and which cannot be treated in the same manner as those patterns. . . .

"In [some] cases the cellular character of the cumuliform cloud patterns is indistinct or missing entirely. . . ."

"In a few cases it was not possible to relate anything in the character of the cumuliform cloud pattern to the surface wind direction. . . ."

Examples of these two types of cases are presented and discussed in [16].

The report also discusses wind information deducible from shearing of cumuliform cloudiness in the immediate post-frontal region, which will be mentioned in the discussion of upper-air winds.

Low-Level Winds in Mature Cyclones: Fritz [7] reports that cloud streets in the interior of a mature cyclone generally parallel the wind, but have some tendency to cross streamlines, converging toward the center. He indicates that this is probably due to little change in wind direction with height. Rutherford [21] states that cloud streets within the clear moat indicate the wind direction at their level. Jones [11], studying a dissipating storm, found a fair to good correlation between cloud bands equatorward and west of the storm center and the mean 1000–700-mb. flow.

UPPER-LEVEL WINDS

Association with Vortices: Nagle and Serebreny [18] found a clear association between the cloud vortex and the pressure center or minimum in the middle and upper troposphere, which of course implies wind relationships at these levels. Sherr [3] obtained similar results, especially for the more mature vortex stages. Serebreny et al. [23] state that: "In general, the large, dense cloud shields associated with vortices in the middle latitudes are oriented along the axis of predominant wind-flow in the lower and middle levels." In the mature cyclone, Fritz [7] reports a concentric band of high winds due to the thermal wind between the outer warm air and the colder inner air (fig. 11).

Trough-Ridge Relationships: Timchalk and Hubert [24] found the bulk of the frontal and vortex associated cloudiness in and ahead of the 500-mb. trough; and from general synoptic experience one should expect the western edge of the frontal cloud band to lie typically somewhat ahead of the 500-mb. trough line. The figures presented by Glaser [8] imply that the western cloud edge lies about along the 500-mb. trough line. Serebreny et al. [23] report: "During situations of strong vortex development when the axis of the upper trough is nearly over the surface low-pressure center, the overrunning prefrontal cloudiness—particularly the cirrus shield—will rarely proceed beyond the upper-level ridge line downstream." Leese [13] states that vortex development, with a spiraling-in of the clear area, is promoted by strong meridional flow ahead of the Low.

Merritt [16] found that:

"a. The 300-mb. trough is located over the east side of the cellular areas to the rear of major cyclones.

"b. The 300-mb. ridge is located in or just to the east of the cloudiness associated with the surface low pressure system.

"c. The amplitude of the troughs and ridges at 300 mb. is proportional to and indicated by the latitudinal extent of interrelated cloud patterns."

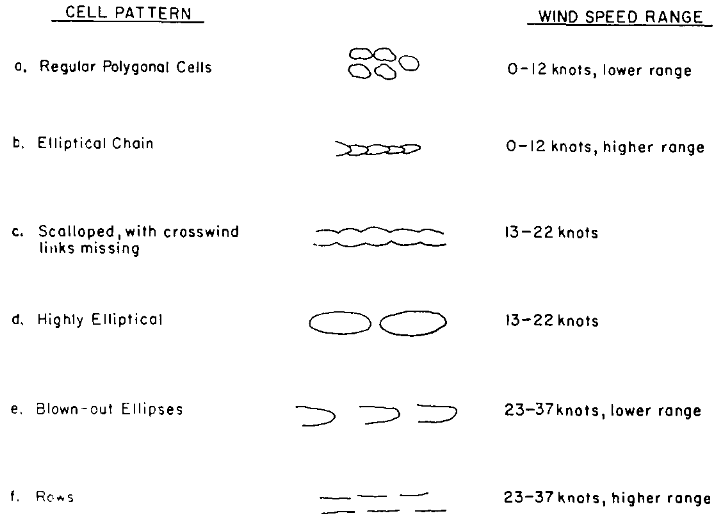

FIGURE 20.—Relationships between cumuliform cell patterns and wind velocity categories in regions to the rear of major cyclones, as determined by C. W. C. Rogers (Merritt [16]).

729-085—64——3

and that ". . . small areas [of cloud cover] indicate short wave lengths and small amplitudes. These small areas are often triangular in shape."

These trough-ridge relationships are illustrated in the schematics in figures 2, 4, 6, 7, 8, 9.

Relationships Near Fronts: When deductions as to the slope of the cold front are possible from the width of the frontal cloud band and/or the location of the front relative to the associated cloudiness, consistency then suggests the most probable orientation of the upper-air wind. To quote Serebreny et al. [23]: "Both katabatic and anabatic frontal cloud formations are observed, particularly with cold fronts. When the cloud mass lies ahead of the cold front with a sharp edge to the cloud system at the frontal boundary (rapid clearing), then the winds aloft are usually normal to the front. When the cloud system lags behind the front, the upper winds are apt to be parallel to the front, at least as far as the clouds extend. Obviously, in an area of sparse data, the precise frontal location is difficult to determine, but if in the analyses one of these conditions is specified, then for reasons of consistency the direction of the upper wind flow appropriate to this condition should be forecast."

Rogers (see Merritt [16]) states: "The occurrence of heavy cumuliform cloudiness in the immediate post-cold frontal region is quite common. Since this region is also one of great vertical shear (i.e., through the frontal surface), it is felt that in some rare cases it should be possible to observe a shearing of the cumuliform cloudiness above the frontal surface in the warm air and thereby the wind direction at that level. . . . When cumuliform clouds penetrate into [such] a frontal zone or other types of conditions where extreme vertical shear exists, the clouds are sheared off. The orientation of the cloudiness is parallel to the wind at the shearing level."

Jet Stream Relationships: Serebreny et al. [23] report that frequently ". . . the jet stream lies nearly overhead [*sic*] the intersection of the polar frontal surface with the 500-mb. level, as has been pointed out previously in the literature.", and that "low level cloud masses may parallel the jet stream." Depending on the frontal slope, the jet stream may be just or well poleward of the frontal cloud band. Winston and Tourville [28] also found the jet stream axis to lie just poleward of the major cloud band. (figs. 1 and 2)

As vortex development is initiated and progresses, Serebreny et al. [23] find that: "With respect to the surface front the jet-stream centrum is displaced [poleward] of the developing-wave stage of a cyclone. In later stages the developing wave moves under the jet-stream centrum and, finally, in the occlusion stage the jet-stream centrum crosses the occlusion near, or slightly [poleward] of, the the point of occlusion." (figs. 1, 2, 3, 4, 6, 7, 8, and 9)

Similar findings are reported by Merritt [16], who states: "The location of the jet stream relative to a vortex varies with the stages of the satellite-observed development pattern:

"1. Open wave—150–200 miles poleward . . . of the broad bright area of the band. Thin bands may indicate the area."

"These thin bands are often difficult to locate because of the lower cellular cloudiness. They are usually found 150–200 miles [poleward] of the major band. It is not yet obvious that the position of the jet stream can be determined outside of the area of the wave, although thin cirriform bands which relate to the jet stream can sometimes be observed." (figs. 1 and 3)

"2. Pre-occlusion [and in the early stage of occlusion]—midway between the center of cloudiness about the vortex and the associated band. An isolated band of bright cloudiness may at times indicate this area." (figs. 3 and 4)

"3. Occlusion—Parallel to and [just] poleward of the major cloud band from a point on the band [equatorward and just west] of the vortex center to just east of the center. A second band of maximum wind is located west of the vortex and parallel to the west and [equatorward] sides of the cloudiness surrounding it." (figs. 6, 7, 8, and 9)

Serebreny et al. [23] further state:

"Since the frontal stages are fairly well delineated in the cloud pictures, the location of the jet stream in the area of vortices involving fronts is fairly readily established from existing front-jet-stream models. However, there are areas away from vortices where the jet stream is considerably displaced from the surface front and its associated cloudiness and may lie over a totally different cloud field from that of a front. In this event the frontal cloud fields yield less exact clues to location of the jet stream aloft. In other words, there is no direct duplication of the entire jet-stream configuration by a unique cloud type or configuration as seen from the satellite. The jet stream may pass over apparently clear as well as cloudy areas, and the total cloud distribution over a wide area must be considered in jet-stream analysis."

Similar departures were noted by Merritt [16], who states that in his ". . . discussion the wind was considered to be parallel if it was directed within 20 degrees of the band orientation. This is not always the case, especially outside of the area specified [in his discussion as quoted above] and in examples which penetrate to low latitudes [equatorward of 30°]. . . . In the case of [a particular] weak pre-occlusion vortex the jet stream has a wide directional deviation from the related cloud band. The shape of the banded area, i.e., narrowing [equatorward and toward the west] may be an indication of these gross variations . . . . The gray appearance of . . . the band suggests a water cloud such as altostratus or altocumulus."

Serebreny et al. [23] also provide certain observed relationships that ". . . will aid in the synoptic interpretation of satellite photographs. Some of these have been embodied in forecasting rules in the past. The more outstanding of these relationships are as follows:

"(1) Where the jet stream is parallel to the cold front, the cloudiness on the cold side of the front usually lies somewhat [equatorward] of the jet stream isotach system—the exact displacement of cloud to jet-stream core varies considerably with the tilt of the isotach system. Where the jet stream is normal to the cold front, direct association of cloud cover to jet-stream orientation is often not apparent. [figs. 1 and 3]

"(2) Jet streams on the east side of a long wave ridge are most apt to lie in clear air. [figs. 4, 6, 7, 8, and 9]. They are usually well organized, with strong horizontal and vertical shear through the front, and pronounced temperature gradients between air masses in the upper levels. These conditions will prevail along the jet stream to the area of the high-level cloud shield downstream, at which point the jet stream and its baroclinic zone usually diminishes [sic].

"(3) When the isotach maximum passes over a high-pressure ridge the cloud system—particularly the cirriform clouds—will be elongated along this maximum and lie on the immediate warm side of the jet stream. Decay of these cloud systems usually occurs on the warm side of the jet-stream exit region.

"(4) The organized state of the jet stream will be weakest over the isentropic moist tongue to the east of a developing vortex, due to weakening of the temperature gradient in the upper levels. This is not to imply that strong winds will disappear, but rather that the horizontal and vertical shear gradients will be lessened."

"(6) As a rule, in a trough behind an occluding cyclone, the maximum-speed portion of the isotach field lies over clear air or over scattered to broken low-level cloud areas, depending upon the stage of cyclone development." (figs. 4, 6, 7, 8, and 9)

In the area west of the cyclone discussed in (6) just above, Madvig [14] reports the jet stream is found forward of the major polygonal clusters of convective cloudiness. (figs. 7, 8, 9)

Miscellaneous Upper-Level Wind Relationships: Bristor and Ruzecki [4] suggest that single, moderately heavy cloud streaks along the wind may be located in areas of cyclonic shear.

Fritz [7] suggests that features in the cloud patterns along the edges of overcast areas may reveal mesoscale cyclonic and anticyclonic eddies.

7. PRECIPITATION

The association between shower activity and brighter cloud areas or large bright cloud elements has been noted by Bristor and Ruzecki [4], Boucher and Newcomb [2], Jones [11], Timchalk and Hubert [24], and Fritz [7]. However, only a low percentage of clouds are accompanied by precipitation, as has been noted by Nagle and Serebreny [18]. A careful study of satellite cloud and radar precipitation data by Nagle [17] indicates that while, over a period of several hours, the integrated radar patterns often show reasonable correlation to the pattern of the brighter clouds, at any instant only a small portion of even a bright cloud is apt to be precipitating. Conover [5] shows several examples of bright clouds of normally non-precipitating types, such as stratocumulus and thick stratus. The failure to establish a relationship between brightness and precipitation may in part be due to premature saturation of the picture brightness scale, with inadequate gray scale differentiation in the brighter areas. On the other hand, there are no good reasons why two cloud masses of similar thickness and composition, one precipitating and one not, should show any striking differences when viewed from above. As yet, no unique characteristics that distinguish precipitating from non-precipitating clouds have been determined. On a probability basis, however, a deep cloud mass (bright) is more likely to precipitate than a shallower, and consequently less bright, one.

FIGURE 21.—Reproduction of figure 10 from Nagle and Serebreny [18]. "Schematic model of the radar precipitation echo distribution around an occluded maritime cyclone. Light stippled area denotes continuous stratiform type precipitation; checked area, area, ragged patches of stratiform type precipitation; solid areas, convective type precipitation; x, pressure vortex center."

Nagle and Serebreny [18] have published a schematic diagram of the radar precipitation echo distribution around an occluded maritime cyclone (reproduced in fig. 21); the distribution they show, which is not strikingly different from that in standard frontal cyclone models published in most meteorological texts, can provide guidance to the more probable areas of precipitation in a satellite-observed cyclone. Their model shows the area of upslope precipitation, due to ascending motion approximately along isentropic surfaces, associated with the cloudy area west and poleward of the storm center, as noted by Bristor and Ruzecki [4].

Madvig [14] has suggested that in the cellular convective cloudiness in the cold air, precipitation is more extensive in areas with clusters of polygonal cells than in those with crescents. This is to be anticipated as a consequence of the lesser shear to be expected in the areas of polygonal cells.

Nagle and Serebreny [18] have observed heavy, persistent, and extensive precipitation in a secondary outlying vortex formed in the cold air flow behind an occluded cyclone. Merritt [16] mentions the probability that periods of deteriorating weather may be associated with the small-scale vortices he observed in the Antarctic.

ACKNOWLEDGMENTS

The many and most helpful criticisms and suggestions, during the preparation of this paper, by Messrs. Roland J. Boucher, Earl S. Merritt, C. W. C. Rogers, and Paul E. Sherr, all of ARACON Geophysics Company, are gratefully acknowledged. The schematics of the various stages of the cloud vortex model were prepared by Mr. James Pike.

REFERENCES

1. T. Bergeron, "A General Survey in the Field of Cloud Physics," International Union of Geodesy and Geophysics, Association of Meteorology, *Ninth General Assembly Memoirs*, Brussels, 1951, pp. 120–134.
2. R. J. Boucher and R. J. Newcomb, "Synoptic Interpretation of Some TIROS Vortex Patterns: A Preliminary Cyclone Model," *Journal of Applied Meteorology*, vol. 1, No. 2, June 1962, pp. 127–136.
3. R. J. Boucher, C. J. Bowley, E. S. Merritt, C. W. C. Rogers, P. E. Sherr, and W. K. Widger, Jr., *Synoptic Interpretations of Cloud Vortex Patterns as Observed by Meteorological Satellites*, Final Report, Contract No. Cwb–10630, ARACON Geophysics Company, Concord, Mass. 1963, 194 pp.
4. C. L. Bristor and M. A. Ruzecki, "TIROS I Photographs of the Midwest Storm of April 1, 1960," *Monthly Weather Review*, vol. 88, Nos. 9–12, Sept.–Dec. 1960, pp. 315–326.
5. J. H. Conover, *Cloud Interpretation from Satellite Altitudes*, CR Research Note 81, Air Force Cambridge Research Laboratories, 1962.
6. J. W. Deardorff, "Satellite Cloud Photos and Large-Scale Vertical Motion," *Journal of Applied Meteorology*, vol. 2, No. 1, Feb. 1963, pp. 173–175.
7. S. Fritz, "Satellite Cloud Pictures of a Cyclone over the Atlantic Ocean," *Quarterly Journal of the Royal Meteorological Society*, vol. 87, No. 373, July 1961, pp. 314–321.
8. A. H. Glaser, *TIROS I: An Operational Evaluation of a New Meteorological Tool*, Second Semi-Annual Summary Report, Contract No. AF 19(604)–5581, Allied Research Associates, Inc., 1960.
9. L. F. Hubert, "Middle Latitudes of the Northern Hemisphere—TIROS Data as an Analysis Aid," *Rocket and Satellite Meteorology*, Proceedings of the First International Symposium on Rocket and Satellite Meteorology, North-Holland Publishing Company, Amsterdam, 1963, pp. 312–316.
10. I. Jacobs-Haupt, "TIROS Observations over the Mediterranean and North Africa," *Rocket and Satellite Meteorology*, Proceedings of the First International Symposium on Rocket and Satellite Meteorology, North-Holland Publishing Company, Amsterdam, 1963, pp. 323–332.
11. J. B. Jones, "A Western Atlantic Vortex Seen by TIROS I," *Monthly Weather Review*, vol. 89, No. 10, Oct. 1961, pp. 383–390.
12. A. F. Krueger and S. Fritz, "Cellular Cloud Patterns Revealed by TIROS I," *Tellus*, vol. 12, No. 1, Feb. 1961, pp. 1–7.
13. J. A. Leese, "The Role of Advection in the Formation of Vortex Cloud Patterns," *GRD Research Notes* No. 78, Air Force Cambridge Research Laboratories, Bedford, Mass., 1962, 27 pp.
14. R. M. Madvig, *Phase II, Nimbus Data-Handling System, Final Report*, Contract No. NAS 5–1882, Stanford Research Institute, 1963. (See Appendix E, Information Content of Satellite Cloud Photographs.)
15. J. S. Malkus, "Cloud Patterns over Tropical Oceans," *Science*, vol. 141, No. 3583, Aug. 30, 1963, pp. 767–778.
16. E. S. Merritt, *Fleet Applications, Meteorological Operational Satellites (Antarctic Area)*, Final Report, Contract No. N189(188)–56507A, ARACON Geophysics Co., Concord, Mass., 1963, 66 pp.
17. R. E. Nagle, *Comparison of Time Integrated Radar Detected Precipitation with Satellite Observed Cloud Patterns*, Scientific Report No. 1, Contract No. AF19(628)–284, Stanford Research Institute, 1962.
18. R. E. Nagle and S. M. Serebreny, "Radar Precipitation Echo and Satellite Cloud Observations of a Maritime Cyclone," *Journal of Applied Meteorology*, vol. 1, No. 3, Sept. 1962, pp. 279–295.
19. V. J. Oliver, "Comparison of a Satellite Nephanalysis with a Conventional Weather Analysis for a Family of Pacific Frontal Storms," *Final Report on the TIROS I Meteorological Satellite System, Technical Report* R–131, National Aeronautics and Space Administration, 1962, pp. 273–279.
20. S. Petterssen, *Weather Analysis and Forecasting, Vol. II, Weather and Weather Systems*, 2d ed., McGraw-Hill Book Co., Inc., New York, 1956, 266 pp.
21. G. T. Rutherford, "Satellite Cloud Photographs—Their Application in Synoptic Analysis," *WMO Bulletin*, vol. 11, No. 4, 1962, pp. 188–194.
22. J. C. Sadler, "Utilization of Meteorological Satellite Cloud Data in Tropical Meteorology," *Rocket and Satellite Meteorology*, Proceedings of the First International Symposium on Rocket and Satellite Meteorology, North-Holland Publishing Company, Amsterdam, 1963, pp. 333–356.
23. S. M. Serebreny, E. J. Wiegman, and R. G. Hadfield, *Investigation of the Operational Use of Cloud Photographs from Weather Satellites in the North Pacific*, Final Report, Contract No. Cwb–10238, Stanford Research Institute, Menlo Park, Calif., 1962, 93 pp.
24. A. Timchalk and L. F. Hubert, "Satellite Pictures and Meteorological Analyses of a Developing Low in the Central United States," *Monthly Weather Review*, vol. 89, No. 11, Nov. 1961, pp. 429–445.
25. M. H. Van Dijk and G. T. Rutherford, "A TIROS III Interpretation Exercise Over Southeast Australia," *Rocket and Satellite Meteorology*, Proceedings of the First International Symposium on Rocket and Satellite Meteorology, North-Holland Publishing Company, Amsterdam, 1963, pp. 305–311.
26. W. K. Widger, Jr., "Examples of Project TIROS Data and Their Practical Meteorological Use," *GRD Research Notes* No. 38, U.S. Air Force Cambridge Research Laboratories, Bedford, Mass, 1960.
27. J. S. Winston, "Satellite Pictures of a Cut-Off Cyclone Over the Eastern Pacific," *Monthly Weather Review*, vol. 88, Nos. 9–12, Sept.–Dec. 1960, pp. 295–314.
28. J. S. Winston and L. Tourville, "Cloud Structure of an Occluded Cyclone over the Gulf of Alaska as Viewed by TIROS I," *Bulletin of the American Meteorological Society*, vol. 42, No 3, Mar. 1961, pp. 151–165.

[*Received January 20, 1964; revised March 30, 1964*]